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Self-regulated Multi-robot Task Allocation

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for the degree of Doctor of Philosophy

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December 2, 2010

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Inspirations

In the Name of Allah, the Most Beneficent, the Most Merciful.

“There is not an animal in the earth, nor a flying creature flying on two wings, but they are peoples like unto you. We have neglected nothing in the Book (of Our decrees). Then unto their Lord they will be gathered.” (Chapter 6, verse:38)

“And your Lord inspired the bees, saying: “Take you habitations in the mountains and in the trees and in what they erect. Then, eat of all fruits, and follow the ways of your Lord made easy (for you)” There comes forth from their bellies, a drink of varying colour wherein is healing for men. Verily, in this is indeed a sign for people who think.” (Chapter 6, verses:68-69)

“ At length, when they came to a (lowly) valley of ants, one of the ants said: “O ye ants get into your habitations, lest Solomon and his hosts crush you (under foot) without knowing it”.” (Chapter 27, verse:18)

“Do they not observe the birds above them, spreading their wings and folding them in? None can uphold them except (Allah) Most Gracious: truly it is He that watches over all things.” (Chapter 67, verse:18)

“The likeness of those who choose other patrons than Allah is as the likeness of the spider when she taketh unto herself a house, and lo! the frailest of all houses is the spider’s house, if they but knew.” (Chapter 29, verse:40)

Source: The Holy Quran. Translation courtesy of <http://quranexplorer.com//Quran/>

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‘Al-hamdu lillahi Rabbil-‘alamin, All the praises and thanks be to Allah, the Rubb of ‘Alamin (the Supreme Lord of mankind, jinn and all that exists) who has endowed man with hearing, seeing, and hearts. May Allah’s peace and blessings be upon His messenger Muhammad, our beloved Prophet and the guide for entire mankind to the straight path, who has taught us to praise the Almighty Allah by saying “*Any matter of importance which is not begun with Al-hamdu lillah (praise be to Allah) remains defective*”¹. So I wholeheartedly thank Almighty Allah for His immense mercy and uncounted blessings upon us on the occasion of the successful completion of this thesis.

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¹Compiled by Al-Imam An-Nawawi in his collection Riyad-us-Saliheen, Book 13 referred from [Abu Dawud].

Abstract

To deploy a large group of autonomous robots in dynamic multi-tasking environments, a suitable multi-robot task-allocation (MRTA) solution is required. This must be scalable to variable number of robots and tasks. Recent studies show that biology-inspired self-organized approaches can effectively handle task-allocation in large multi-robot systems. However most existing MRTA approaches have overlooked the role of different communication and sensing strategies found in self-regulated biological societies.

This dissertation proposes to solve the MRTA problem using a set of previously published generic rules for division of labour derived from the observation of ant, human and robotic social systems. The concrete form of these rules, the *attractive field model* (AFM), provides sufficient abstraction to local communication and sensing which is uncommon in existing MRTA solutions.

This dissertation validates the effectiveness of AFM to address MRTA using two bio-inspired communication and sensing strategies: “global sensing - no communication” and “local sensing - local communication”. The former is realized using a centralized communication system and the latter is emulated under a peer-to-peer local communication scheme. They are applied in a manufacturing shop-floor scenario using 16 e-puck robots. A robotic interpretation of AFM is presented that maps the generic parameters of AFM to the properties of a manufacturing shop-floor. A flexible multi-robot control architecture, *hybrid event-driven architecture on D-Bus*, has been outlined which uses the state-of-the-art D-Bus interprocess communication to integrate heterogeneous software components.

Based-on the organization of task-allocation, communication and interaction among robots, a novel taxonomy of MRTA solutions has been proposed to remove the ambiguities found in existing MRTA solutions. Besides, a set of domain-independent metrics, e.g., plasticity, task-specialization and energy usage, has been formalized to compare the performances of the above two strategies. The presented comparisons extend our general understanding of the role of information exchange strategies to achieve the distributed task-allocations among various social groups.

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List of Acronyms

AFM	attractive field model
AGV	automated guided vehicle
APCD	average production completion delay
APMW	average pending maintenance work-load
BMS	biology-inspired manufacturing system
CCD	charge-coupled device
DEM	data and event management
DOL	division of labour
GigE	Gigabyte Ethernet
GIL	Global Interpreter Lock
GSNC	global sensing - no communication
HEAD	hybrid event-driven architecture on D-Bus
IPC	inter-process communication
LPCM	local peer-to-peer communication model
LSLC	local sensing - local communication
MOM	maintenance only mode
MRS	multi-robot system
MRTA	multi-robot task allocation
P2P	peer-to-peer
PMM	production and maintenance mode
RCC	robot-controller client
SDK	software-development kit
SHM	shared memory
TPS	task perception server

1.1 Issues in multi-robot task allocation

Researchers in the field of robotics generally agree that multiple robots can perform complex and distributed tasks more conveniently. Multi-robot systems can provide improved performance, fault-tolerance and robustness in those tasks through parallelism and redundancy (Arkin 1998, Parker and Tang 2006). In last two decades, multi-robot system has been considered for many challenging applications. For example, multi-robot systems can be used in: large space monitoring tasks, e.g. underwater environment monitoring (Eriksen et al. 2001), dangerous tasks e.g., robotic de-mining (Dunbar and Klein 2002), tasks that scale-up or scale-down over time, e.g. factory automation (Wurman et al. 2008), and so forth.

In order to get potential benefits of multi-robot systems, one needs to answer a common research question. *How can the tasks be allocated among multiple robots dynamically?* In robotics, this is called *multi-robot task allocation* (MRTA) (Gerkey and Mataric 2004). This issue can be treated as the *division of labour* (DOL) among robots, analogous to the DOL in biological and human social systems (Sendova-Franks and Franks 1999). Although the term “division of labour” is often used in biological literature and the term “task-allocation” is primarily used in multi-agent literature, both of these terms carry similar kinds of meanings with slightly different semantics. Here, these terms have been used interchangeably.

MRTA is generally identified as the question of assigning tasks in an appropriate time to the appropriate robots considering the changes of the environment and/or the performance of other team members (Gerkey and Mataric 2003). This is a *NP-hard* optimal assignment problem where optimum solutions cannot be found quickly for large and complex problems (Parker 2008). Here NP-hard, abbreviated from non-deterministic polynomial-time hard, is a class of problems that are “at least as hard as the hardest problems in NP” (Garey and Johnson 1979).

The complexities of the distributed MRTA problem arise from the fact that there is no central planner or coordinator for task assignments, and in large multi-robot systems, generally robots have limited capabilities to sense, to communicate and to interact locally. None of them has complete knowledge of the past, present or future actions of other robots. Moreover, they do not have the complete view of the world state. The computational and communication bandwidth requirements also restrict the solution quality of the problem (Gerkey and Mataric 2004).

Researchers from multi-robot and multi-agent systems, operations research and other disciplines have approached the task-allocation issue in many different ways. Traditionally, task allocation in multi-agent systems have been divided into two major categories: i) predefined and ii) bio-inspired self-organized task-allocation (Shen et al. 2001).

Early research on predefined task-allocation was dominated by intentional co-operation (Parker 2008), use of dynamic role assignment (Chaimowicz et al. 2002) and market-based bidding approach (Dias et al. 2006). Under these approaches, robots use direct task-allocation method, often to communicate with group members for negotiating on tasks. These approaches are intuitive, comparatively straight forward to design and implement, and can be analysed formally. However, these approaches typically work well only when the number of robots are small (≤ 10) (Lerman et al. 2006).

On the other hand, self-organized task-allocation approach relies on the emergent group behaviours, such as emergent cooperation (Kube and Zhang 1993), adaptation rules (Liu et al. 2007). They are more robust and scalable to large team sizes. However, most of the robotic researchers found that self-organized task-allocation approach is difficult to design, to analyse formally and to implement in real robots. The solutions from these systems are also sub-optimal. It is

also difficult to predict exact behaviours of robots and overall system performance.

Within the context of the Engineering and Physical Sciences Research Council (EPSRC) project, “Defying the Rules: How Self-regulatory Systems Work”, the above mentioned self-regulated DOL problem has been tackled in an alternate way (Arcaute et al. 2008). This approach has been inspired from the studies of emergence of task-allocation in both biological and human social systems. These studies show that a large number of species grow, evolve and generally continue functioning well by the virtue of their individual self-regulatory DOL systems.

The amazing abilities of biological organisms to change, to respond to unpredictable environments, and to adapt over time lead them to sustain life through biological functions such as self-recognition, self-recovery, self-growth etc. It is interesting to note that in animal societies task-allocation has been accomplished year after year without a central authority or an explicit planning and coordinating element. Direct and indirect communication strategies are used to exchange information among individuals (Camazine et al. 2001).

The decentralized self-growth of Internet and its bottom-up interactions of millions of users around the globe present similar evidence of task-allocation in human social systems (Andriani and Passiante 2004). These interactions of individuals happen in the absence of, or in parallel with, strict hierarchy. Moreover from the study of sociology (Sayer and Walker 1992), cybernetics (Beer 1981), strategic management (Kogut 2000) and related other disciplines it is found that decentralized self-regulated systems exist in nature and in man-made systems which can grow and achieve self-regulated DOL over time by the virtue of their common bottom-up rules of self-regulation.

From the above mentioned multi-disciplinary studies of various complex systems, four generic rules have been proposed in order to explain self-regulation in social systems. These four rules are: *continuous flow of information*, *concurrency*, *learning* and *forgetting*, all of them will be explained in Chapter 5. Primarily these rules deal with the issue of deriving local control laws for regulating an individual’s task-allocation behaviour that can facilitate the DOL in the entire group. In order to employ these rules in the individual level, a formal model of self-regulated DOL has been developed. AFM provides an abstract framework for self-regulatory DOL in social systems. However, without a proper validation in a real robotic system, it

is not possible to claim its applicability to the above MRTA problem. Particularly, the following two questions have been raised.

1. Can the AFM be adopted to solve the above MRTA problem for a relatively large group of real robots?
2. Can the AFM be made relevant for industrial scenarios as well as for the emulation of biological tasks?

The first question demands to evaluate the very basic capabilities of AFM, i.e. whether it can provide the basic form of DOL in large groups. As it is well known that conducting real robotic experiments with large number of robots is time consuming and resource intensive, in this study the term “large group of robots” is used to mean a group with at least 10 or more robots¹. It has been hypothesized that AFM can be used as a distributed task-allocation mechanism for a large group of robots. It should be capable of providing all the basic task-allocation facilities, e.g. plasticity in task-allocation, task-specialization, as discussed in detail in Sec. 2.1.3.

The second question puts AFM under a big challenge. Traditionally, researchers in the area of robotics, who use self-organized task-allocation methods, limit their experiments to test if their models can sufficiently imitate biological tasks, e.g., foraging (Krieger and Billeter 2000) or prey-retrieval (Labella 2007). These experiments simply match the biological DOL models with their robotic counterparts. However, it has been hypothesized that AFM can work under real task settings where multiple tasks should be served by multiple-robots concurrently. It has been assumed that even if the robots do not perform specific complex industrial tasks with sophisticated hardware modules, AFM can still be used to find the high-level task-allocation performance by mimicking any suitable industrial task. This high-level task-allocation performance can be used as an indication of the validity of AFM for putting it in real-world applications.

The outcome of this research can be applied to solve generic task-allocation problem in numerous multi-agent systems. Generally AFM can be used as a generic framework for DOL in various social systems and particularly, the outcome

¹ Although this is very difficult to specify a certain number for defining “large”, a consensus has been found with some other researchers, (e.g. Lerman et al. 2006) that a large group of robots currently stands for roughly 10 or more robots.

of this research can be relevant to design appropriate MRTA solution of large multi-robot systems in order to perform real industrial tasks. For example, this technique can potentially contribute to make multi-robot systems more useful for automated material handling tasks in warehouses or in manufacturing industries. Since last decade these industries have been facing all the existing challenges of traditional centralized and sequential manufacturing processes e.g. changing the manufacturing plant layouts on-the-fly, adapting for high variation in product styles/quantities, and dynamic allocation of active manufacturing resources e.g., robots and automated guided vehicles (AGVs) (Shen et al. 2006).

1.2 Communication and sensing strategies for task allocation

In biological social systems, communications among the group members, as well as sensing the task-in-progress, are two key components of self-organized DOL. In robotics, existing self-organized task-allocation methods rely heavily upon local sensing and local communication of individuals for achieving self-organized task-allocation. However, AFM differs significantly in this point by avoiding the strong dependence on the local communication and interaction found in many existing approaches to MRTA. AFM requires a system-wide continuous flow of information about tasks, agent states etc. But this can be achieved by using both centralized and decentralized communication modes under explicit and implicit communication strategies. Chapter 3 reviews these communication modes and strategies with necessary details.

In order to enable continuous flow of information in a multi-robot system, two types of sensing and communication strategies have been implemented inspired by the self-regulated DOL found in two types of social wasps: *polistes* and *polybia* (Jeanne 1999). Depending on the group size, these species follow different strategies for communication and sensing of tasks. *Polistes* wasps are called the *independent founders* in which reproductive females establish colonies alone or in small groups (in the order of 10^2), but independent of any sterile workers. On the other hand, *polybia* wasps are called the *swarm founders* where a swarm of workers and queens initiate colonies consisting of several hundreds to millions of

individuals.

The most notable difference in the organization of work of these two social wasps is: independent founders do not rely on any cooperative task performance while swarm founders interact with each-other locally to accomplish their tasks. The work mode of independent founders can be considered as *global sensing - no communication (GSNC)* where the individuals sense the task requirements throughout a small colony and do these tasks without communicating with each other. On the other hand, the work mode of swarm founders can be treated as *local sensing - local communication (LSLC)* where the individuals can only sense tasks locally due to large colony-size and they can communicate locally to exchange information, e.g. task-requirements (although their exact mechanism is unknown).

In this study, these two sensing and communication strategies have been used to compare the performance of the self-regulated DOL of a large group of robots under AFM. The research questions behind putting these strategies into action are as follows.

1. Is it the case that task-allocation through GSNC strategy should be limited only to small group of robots, like polistes wasps?
2. Does the task-allocation performance in large groups significantly vary under GSNC and LSLC strategies?

Regarding the first question, if the self-regulated DOL in a large group of robots is not achieved by following GSNC strategy, it should be concluded that this strategy is inappropriate for a large group. The second question quantitatively investigates the variations of performance due to the use of different communication and sensing strategies. The findings from this comparative study of different bio-inspired communication and sensing strategies can be very useful for designing efficient MRTA solutions. Based on these findings assertions can be made, both quantitatively and qualitatively, whether local communication and local interaction should be considered as the prerequisites to achieve self-regulated DOL in large groups of robots.

1.3 Summary of individual contributions

The main individual contributions made by the author of this thesis, are as follows:

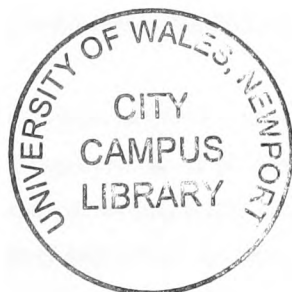
- **Interpretation of AFM, an inter-disciplinary generic model of DOL, as a basic mechanism of self-regulated MRTA.** Although AFM has been developed as a part of a collaborative EPSRC research project, the author of this thesis has interpreted it for multi-robot systems with an example illustration under a manufacturing shop-floor scenario. This concrete interpretation is original and separate from the abstract descriptions of AFM provided by the EPSRC project members.
- **Validation of the model through experiments with reasonably large number of real robots i.e., 16 e-puck robots.** Although AFM was constructed under the EPSRC project collaboration, no solid methodology was given to validate it. Hence the author has proposed and formalized the necessary observables and parameters to validate AFM.
- **Comparisons of the performances of two bio-inspired sensing and communication strategies in achieving self-regulated MRTA.** This is solely contributed by the author since AFM does not provide any framework for realizing communication among the individuals of a social group.
- Development of a flexible multi-robot control architecture using D-Bus inter-process communication technology. This is an original contribution of the author towards developing a flexible multi-robot control framework.
- Classification of MRTA solutions based on three major axes: organization of task-allocation, interaction and communication. The author has conceived this taxonomy and has provided necessary explanations.

1.4 Thesis outline and relevant publications

This thesis has been organized as follows. Chapter 2 and 3 review the related literature on general science and multi-robot systems respectively. Chapter 3 also presents a novel taxonomy of MRTA solutions and discusses the related work on communication in multi-robot systems within the context of self-regulated MRTA. Chapter 4 reviews experimental tools and technologies used in this dissertation. Chapter 5 describes the validation of AFM in a multi-robot system under the

GSNC strategy and discusses the findings from the self-regulated MRTA experiments. Chapter 6 presents the work on using AFM under the LSLC strategy and compares the performance of self-regulated task-allocation under both GSNC and LSLC strategies. Chapter 7 draws conclusions, summaries and presents the possibilities for future work. The following publications are relevant to this thesis.

- Md Omar Faruque Sarker and Dahl Torbjorn S. *A Robotic Validation of the Attractive Field Model: An Inter-disciplinary Model of Self-regulatory Social Systems*. In the Proceedings of the International Conference on Swarm Intelligence (ANTS 2010), LNCS 62354, Marco Dorigo, Mauro Birattari, Gianni A. Di Caro, Ren Doursat, Andrieas P. Engelbrecht, Dario Floreano, Luca Maria Gambardella, Roderich Gro, Erol ahin, Hiroki Sayama, Thomas Sttzle (Eds.), Springer, pp 24-35, Brussels, Belgium, September 8-10, 2010.
- Md Omar Faruque Sarker and Dahl, Torbjorn S. *Flexible Communication in Multi-robotic Control System Using HEAD: Hybrid Event-driven Architecture on D-Bus*. In the Proc. of the UKACC International Conference on Control (CONTROL 2010), pp 926-931, Coventry, UK, September 7-10, 2010.
- Md Omar Faruque Sarker and Torbjorn S. Dahl. *Bio-inspired Communication for Self-regulated Multi-robot Sytems*. Multi-Robot Systems, Trends and Development, I-Tech Publisher, Vienna, Austria, *to appear*, 2010.



2.1 Definition of key terms

2.1.1 Self-regulation

Animals and flying beings, that live on or above earth, form social communities similar to human societies (Ali 1995). In recent years, the study of biological social insects and other animals reveals to us that simple individuals of these self-organized societies can solve various complex and large everyday-problems with a few behavioural rules, relying on their minimum sensing and communication abilities (Camazine et al. 2001). Some common tasks of these biological societies include: dynamic foraging, building amazing nest structures, maintaining division of labour among workers (Bonabeau et al. 1999). These tasks are done by colonies ranging from a few animals to thousands or millions of individuals. Despite their huge colony size, they easily achieve surprising efficiency in those tasks with many common features, e.g. robustness, flexibility, synergy (for an example in ants, see Fig. 2.1).

Today, these findings have inspired scientists and engineers to use this knowledge of biological self-organization in developing solutions for various problems of artificial systems, such as routing traffic in telecommunication and vehicle networks, designing control algorithms for large groups of autonomous robots, automating industrial shop-floor tasks and so forth (Garnier et al. 2007).

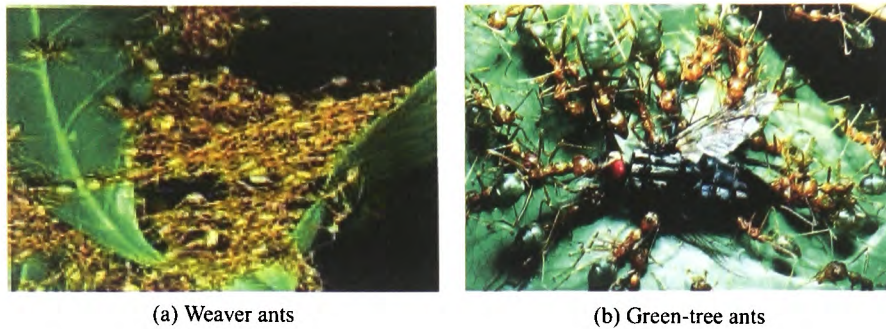


Figure 2.1: (a) During nest construction, weaver ants combine two leaves by pulling them from two sides Yahya (2000). (b) Green-tree ants retrieve a large-prey.
<http://www.spacecollective.org>, last seen on 01/05/2010.

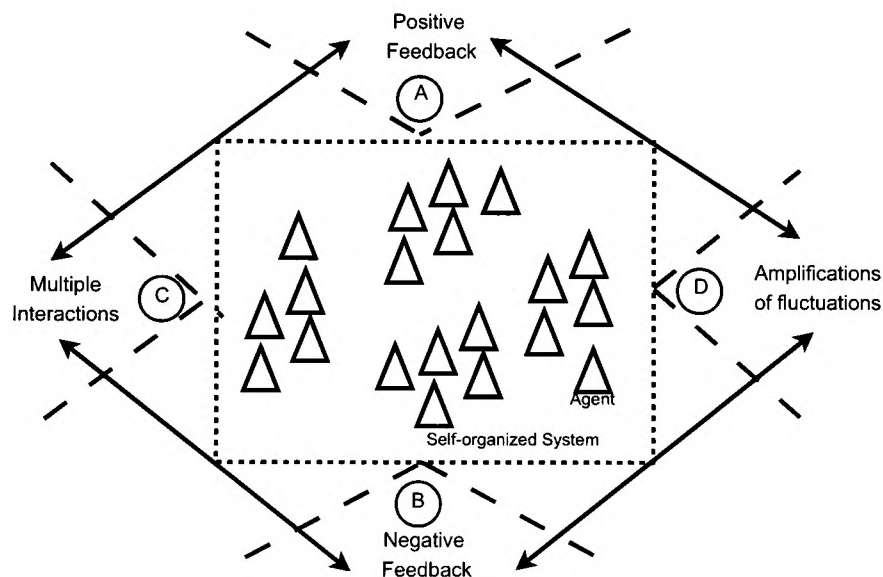


Figure 2.2: Self-organization viewed from four (A-D) inseparable perspectives. Adopted from Camazine et al. (2001).

Self-organization, in biological and other systems, is often characterized in terms of four major ingredients: 1) positive feedback, 2) negative feedback, 3) presence of multiple interactions among individuals and their environment, and 4) amplification of fluctuations e.g., random walks, errors, random task-switching (Camazine et al. 2001). As shown in Fig. 2.2, an external observer, as if looking through transparent glasses, can recognize a self-organized system by observing

the individual interactions of that system from four interlinked perspectives.

The first perspective is the *positive feedback* or amplification that can be resulted from the execution of simple behavioural “rules of thumb”. For example, recruitment to a food source through trail laying and trail following in some ants is due to the positive feedback that attract other ants to follow the trail and to lay more pheromones over time. The second perspective is the *negative feedback* that counterbalances positive feedback. This usually occurs to stabilize collective patterns, e.g., crowding at the food sources (saturation), competition between paths to food sources etc. The third perspective is the *presence of multiple interactions* that can be direct peer-to-peer (P2P), broadcast or indirect *stigmergic*, e.g. ants’ pheromone laying. Finally, the fourth perspective is the *amplification of fluctuations* that comes from various stochastic events. For example, errors in trail following of some ants may lead some foragers to get lost and later on, to find new and unexploited food sources, and recruit other ants to those sources.

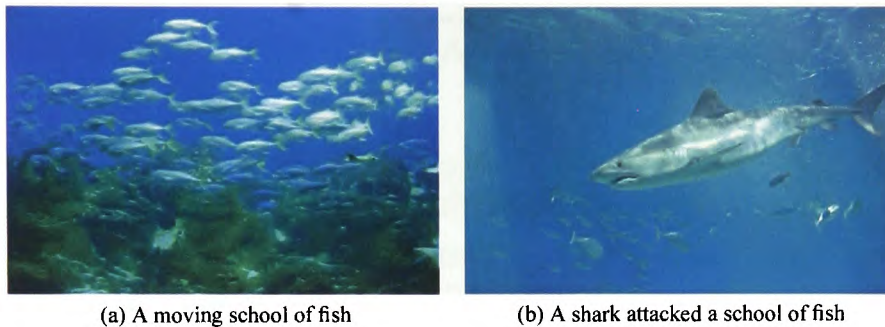


(a) Honey-bee nest



(b) Construction of honey-combs

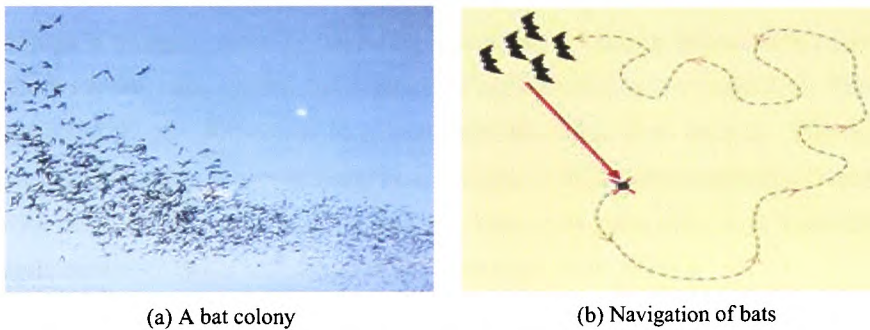
Figure 2.3: (a) A Honey-bee colony has built a nest on a tree-branch. From <http://www.harunyahya.com>, last seen on 01/05/2010. (b) Honey-bees are constructing honey combs. From <http://knol.google.com>, last seen on 01/05/2010.



(a) A moving school of fish

(b) A shark attacked a school of fish

Figure 2.4: (a) Group cohesion of a school of fish. (b) When a shark attacks a school of fish, they misguide the attacker by swift random movements. From <http://www.travelblog.org> last seen on 01/05/2010.



(a) A bat colony

(b) Navigation of bats

Figure 2.5: (a) One of the largest bat colony with about 50 million bats, (b) These bats can show amazing navigation abilities: they always fly back to their nest on a straight route from wherever they are, reproduced from Tuttle (1995).

In a self-organized system, an individual agent may have limited cognitive, sensing and communication capabilities. But they are collectively capable of solving complex and large problems, e.g. coordinated nest construction of honey-bees (Fig. 2.3), collective defence of school of fishes from a predator attack (Fig. 2.4), ordered homing of bats (Fig. 2.5). Since the discovery of these collective behavioural patterns of self-organized societies, scientists observed modulation or adaptation of behaviours in the individual level (Garnier et al. 2007). For example, in order to prevent a life-threatening humidity-drop in the colony, cockroaches maintain a locally sustainable humidity level by increasing their tendency to aggregate, i.e. by regulating their individual aggregation behaviours.



Figure 2.6: Three major interfaces of a self-regulated agent.

As shown in Fig. 2.6, the self-regulation of an individual agent is depicted through a triangle where its base-arm represents the simple behavioural rules of thumb (in this case, intense aggregation of cockroaches in low humidity). This is supported by two side-arms: local communication and local sensing. This local sensing is sometimes also referred to as sensing or information gathering from the work in progress, e.g. stigmergy and this local communication is an instance of direct communication with neighbours (Camazine et al. 2001).

Self-regulation has been studied in many other branches of knowledge. In most places of literature, self-regulation refers to the exercise of control over oneself to bring the self into line with preferred standards (Baumeister and Vohs 2007). One of the most notable self-regulatory process is the human body's homoeostatic process where the human body's inner process seeks to return to its regular temperature when it gets overheated or chilled. Baumeister and Vohs (2007) has referred self-regulation to goal-directed behaviour or feedback loops, whereas self-control may be associated with conscious impulse control.

In psychology, self-regulation denotes the strenuous actions to resist temptation or to overcome anxiety. In this domain, self-regulation is broadly divided into two categories: i) conscious and ii) unconscious self-regulation. Conscious self-regulation puts emphasis on conscious and deliberate efforts in self-regulation. On the other hand, unconscious self-regulation refers to the automatic self-regulatory process that is not labour intensive but operate in harmony with unpredictable and unfolding events in the environment. This process uses the available informational input in ways that help to attain an activated goal.

The concept of self-regulation is also common in cybernetic theory where self-regulation in inanimate mechanisms shows that they can regulate themselves by making adjustments according to pre-programmed goals or set standards. A common example of this kind can be found in a thermostat that controls a heating and cooling system to maintain a desired temperature in a room. In physics, chemistry, biology and some other branches of natural sciences, the concept of self-regulation is centred around the study of self-organizing individuals.

Self-regulation has also been studied in the context of human social systems. Here it is originated from the division of social labour that creates self-organized processes with self-regulating effects (Kppers et al. 1990). Two types of self-regulation have been reported in many places of sociology literature: i) self-regulation from self-organization and ii) self-regulation from activities of components in a heterarchical organization. It is interesting to note that self-regulation in biological species provides similar evidence of bottom-up approach to self-regulation of heterarchical organization through the interaction of individuals in the absence, or in parallel, of strict hierarchy (Beer 1981).

From the above discussion, it is clear that the term *self-regulation* carries a wide range of meanings in different branches of knowledge. In psychology and cognitive neuroscience, self-regulation is discussed solely within an individual's perspective whereas, in biology and social sciences, self-regulation is discussed within the context of a group of individuals or society as a whole. In this thesis, the latter context is more appropriate where self-regulation focuses on monitoring an individual's own state and environmental changes, in relation to the communal goal and, in turn, this leads to adjust the behaviours of that individual with respect to the changes found.

2.1.2 Communication

What is Communication? Defining *communication* can be challenging due to the use of this term in several disciplines with somewhat different meanings. This has been portrayed in the writing of Sarah Trenholm (Richard West 2003) who describes communication as a piece of luggage overstuffed with all manners of odd ideas and meanings. Richard West (2003) defines communication as:

“A social process where individuals employ symbols to establish and

interpret meaning in their environment.”

The notion of being a “social process” involves, at least two or more individuals engaged in dynamic and ongoing interactions. Moreover, symbols can be simply some sort of arbitrary labels given to a phenomena and they can represent concrete objects or abstract ideas.

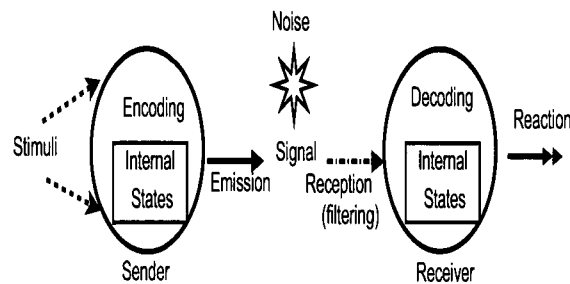


Figure 2.7: A biological model of communication, adopted from Frings (1977).

According to a biological model of communication (Fig. 2.7), communication is a biological process where an individual (sender) intentionally transmits encoded message through a physical signal and that, on being received and decoded by another individual of same species (receiver), influences receiver's behaviour (Frings 1977). Note that, here individuals are of same species and thus they have a shared message vocabulary and mechanism of message encoding/decoding. Although this definition has not included the dynamics of a communication process, it is more precise for low-level biological and artificial systems. It accounts for the behavioural changes during communication process. These changes can be tracked through observing states of individuals.

Models of Communication. The elements of communication can be analysed to find the whole picture involved in an individual's communication and sensing process. This can be explained through the study of the models of communication. There exists plenty of models of communication. Here three prominent models: i) linear model, ii) interaction model and iii) transaction model, have been discussed briefly.

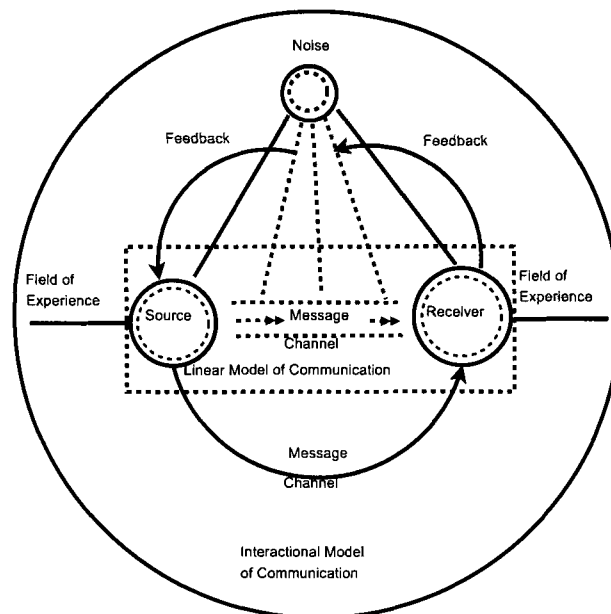


Figure 2.8: General models of communication, adopted from Richard West (2003).

Fig. 2.8 embeds first two models inside a single circle. The linear model is shown by dashed lines. This model was introduced by Claude Shanon and Warren Weaver in 1949. Here communication is a one way process where a *message* is sent from a *source* to a *receiver* through a *channel*.

In Fig. 2.8, around the linear model, interaction model has been drawn. This model, proposed by Wilber Schramm in 1954, views communication as a two-way process that uses an additional *feedback* element linking both source and receiver. This feedback is a response given to the source by the receiver to confirm how the message is being understood. Here, during message passing, both source and receiver utilize their individual *field of experiences* that describe the overlap of their common experiences, cultures etc.

Unlike separate field of experiences and discrete sending and receiving of messages, in the transactional model, introduced by Barnlund in 1970, the sending and receiving of messages are done simultaneously. Here, the field of experiences of source and receiver can overlap to some degree. In all of the above three models, *noise* or a common message distorting element is present in the communication process. This noise can occur from the linguistic influences, i.e. message seman-

tics, physical or bodily influences, cognitive influences or even from biological or physiological influences e.g., anger or shouting voice while talking.

The above models of communication describe the incremental complexities of message exchanging in the communication process. Surely, the transactional model is the most elegant model that prescribes adjusting the sender's message content while receiving an implicit or explicit feedback in real-time. For example, while advising her son to read a story book, a mother may alter her verbal message as she simultaneously "reads" the non-verbal message from her child's face.

However, in case of a multi-robot system, such sophistication in communication may not be required or realizable by the current state-of-the-art in multi-robot communication technology. In this study, a simple linear model has been adopted. This meets the necessary communication requirements of a multi-robot system. The feedback has not been considered as it is assumed that all robots of an artificial multi-robot system have a common shared vocabulary such that a message is understood as it is sent.

Communication modes and strategies. The communication structure of a system can broadly be classified into two major categories: centralized communication and decentralized or local communication. A centralized communication system generally has a central entity, e.g. a gateway, that routes all incoming and outgoing communications. Individual nodes of this system often do not communicate with each other directly. But they can send and receive messages through this central gateway. This central entity can play other roles, such as access control, resource allocation and so on. On the other hand, in local communication, there is no central entity and each node can independently route messages to others.

In both biological and robotic literature two basic types of communication are often discussed: 1) direct or explicit communication and 2) indirect or implicit communication. *Direct communication* is an intentional communicative act of message passing that aims at one or more particular receiver(s) (Mataric 1998). It typically exchanges information through physical signals.

In contrast, *indirect communication*, sometimes termed as *stigmergy* in biological literature, happens as a form of modifying the environment, e.g. pheromone dropping by ants (Bonabeau et al. 1999). In an ordinary sense, this is an observed behaviour and many robotic researchers call it as *no communication* (Labella 2007).

In order to avoid ambiguity, in this dissertation, the term *communication*, always represents *direct* communication.

Direct or explicit communication can be limited by a communication range and thus by a number of target recipients. Under both centralized and local communication, nodes can select a certain number of target recipients of their messages. This process specifies *to whom* a node intends to communicate. In this thesis, this mechanism of target recipient(s) selection has been denoted as *communication strategy*.

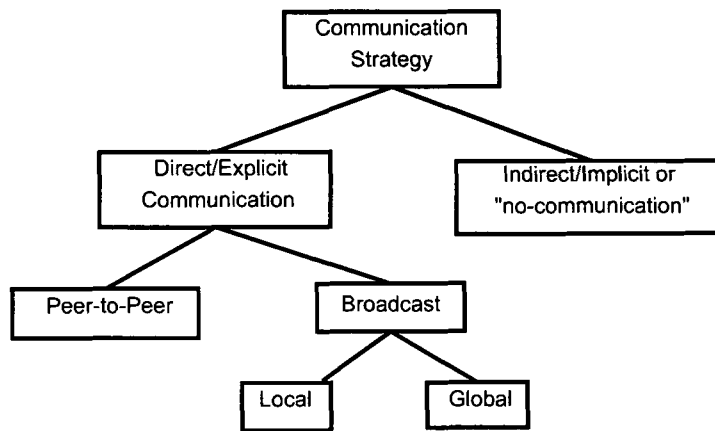


Figure 2.9: Common communication strategies observed in social systems.

Fig. 2.9 shows the most common communication strategies found in a social system. In the simplest case, when only two nodes can communicate this becomes P2P communication. When nodes can spread information to a limited number of peers of their locality, the communication takes the form of *local broadcast*, i.e. one sender and a few receivers within a certain locality. For example, when a foraging honey-bee gives the information of flower sources to a number of peers through various dances, it conveys this information to a few peers through a local broadcast. However, giving the sample of nectar through tactile or taste to its peers can be considered as an instance of P2P communication. The *global broadcast* strategy can be found in almost all social species to handle emergency situations, e.g. emitting alarm signal in danger.

Table 2.1: General characteristics of common communication modes

Type	Indirect or implicit communication	Direct or explicit communication
Centralized Communication	Typically a central entity modifies the environment. It facilitates passive forms of communications, i.e. communication without specific target recipient.	Both global & local broadcast communication are commonly used. P2P communication can also occur. Here, exchange of messages occurs through a central entity.
Decentralized or Local Communication	All individuals are free to modify the environment and convey information to others.	P2P and local-broadcast are most common. Global broadcast occurs to handle an emergency. All communications are local without having a central entity.

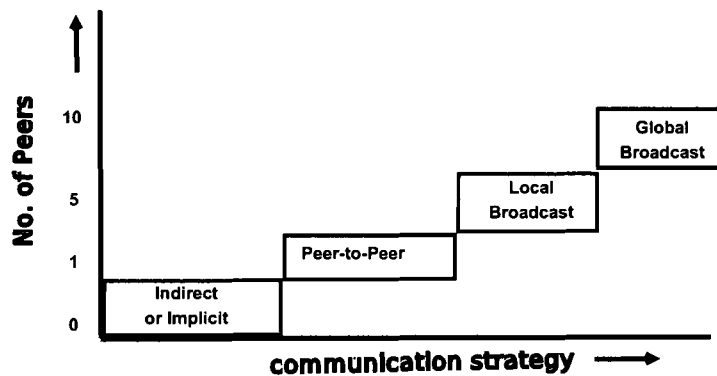


Figure 2.10: Number of recipients involved in various communication strategies.

Table 2.1 shows the relationship between various communication modes and their ways of adopting different strategies. Fig. 2.10 shows a typical count of average number of peers in various communication strategies. The actual number of peers under local broadcast strategy depends on a particular social system and it changes over time in different levels of interactions among individuals. Sec. 2.2 and 3.3 review communication in biological social systems and multi-robot systems respectively.

2.1.3 Division of labour or task-allocation

Encyclopaedia Britannica (2010) serves the definition of *division of labour* as the “separation of a work process into a number of tasks, where each task is performed by a separate person or a group of persons”. Originated from economics and sociology, the term division of labour is widely used in many branches of knowledge. As mentioned by the Scottish philosopher Adam Smith, the founder of modern economics:

The great increase of the quantity of work, which in consequence of the division of labour the same number of people are capable of performing, is owing to three different circumstances; firstly, to increase the dexterity in every particular workman; secondly, to the saving of the time which is commonly lost in passing from one species of work to another; and lastly, to the invention of a great number of machines which facilitate and abridge labour, and enable one man to do the work of many. (Adam Smith (1776) in Sendova-Franks and Franks (1999))

In sociology, DOL usually denotes the work specialization (Sayer and Walker 1992). Basically, it answers three major questions:

1. *What task?* This gives the description of the tasks to be done, service to be rendered or products to be manufactured.
2. *Why dividing it to individuals?* This states the underlying social standards for this division, such as task appropriateness based on class, gender, age, skill etc.
3. *How to divide it?* This relates to the method or process of separating the whole task into small pieces of tasks that can be performed easily.

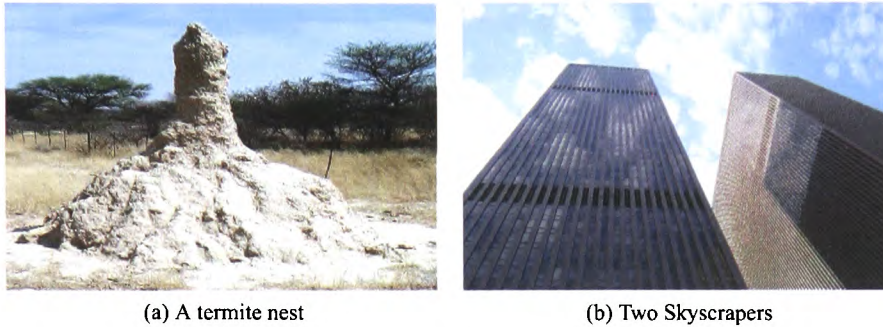


Figure 2.11: (a) A termite colony constructs their nest through bottom-up approach, i.e. without a central planner. (b) Humans construct skyscrapers using a top-down plan. From <http://www.harunyahya.com>, last seen on 01/05/2010.

DOL is commonly observed in social insects, such as in termites (Fig. 2.11(a)), ants, honey-bees and other biological societies. Two major metrics of DOL have been established in literature: i) task specialization and ii) plasticity. *Task specialization* is an integral part of DOL where a worker usually does not perform all tasks, but rather specializes in a set of tasks, according to its morphology, age, or chance (Bonabeau et al. 1999). This DOL among nest-mates, whereby different activities are performed simultaneously by groups of specialized individuals, is believed to be more efficient than if tasks are performed sequentially by unspecialised individuals.

DOL is also characterized by *plasticity* which means that the removal of one class of workers is quickly compensated for by other workers. Thus distributions of workers among different concurrent tasks keep changing according to the external (environmental) and internal conditions of a colony (Garnier et al. 2007).

In artificial social systems, like multi-agent or multi-robot system, the term “division of labour” is often found synonymous to “task-allocation” (Shen et al. 2001). However, some researchers argued to distinguish these terms due to the origin and particular contextual use of these terms (Labella 2007). Particularly, DOL adopts the biological notion of collective task performance with little or no communication. On the other hand, task allocation follows the meaning of assigning task(s) to particular robot(s) based on individual robot capabilities, typically through explicit communication, such as *intentional cooperation* (Parker 1998). Generally, the former is considered by *swarm robotic system* and latter is done under *tradi-*

tional multi-robot system. Sec. 3.1 covers both of these approaches and Sec. 3.2 provides critical reviews on DOL under these approaches.

In this dissertation, in order to define DOL, the biological approach has been adopted that emphasizes on having task-specialization and plasticity among workers. However, no restriction on the use of communication has been imposed. In fact, DOL has been viewed as a group-level phenomenon which occurs due to the individual agent's self-regulatory task-allocation behaviour. AFM, the model of self-regulated DOL used in this thesis, provides necessary abstractions to the communication and sensing processes of individuals that are discussed in detail in Chapter 5 and 6.

2.2 Communication in biological social systems

Communication plays a central role in self-regulated DOL of biological social systems. In this section, communication among social insects are briefly reviewed.

2.2.1 Purposes, modalities and ranges

Communication in biological societies serves many closely related social purposes. Most P2P communication include: recruitment to a new food source or nest site, exchange of food particles, recognition of individuals, simple attraction, grooming, sexual communication etc. In addition to that colony-level broadcast communication include: alarm signal, territorial and home range signals and nest markers, communication for achieving certain group effect such as facilitating or inhibiting a group activity (Holldobler and Wilson 1990).

Biological social insects use different modalities to establish social communication, such as sound, vision, chemical, tactile, electric and so forth (Table 2.2). Sound waves can travel a long distance and thus they are suitable for advertising signals. They are also best for transmitting complicated information quickly (Slater 1986). Visual signals can travel more rapidly than sound, but they are limited by the physical size or line of sight of an animal. They also do not travel around obstacles. Thus they are suitable for short-distance private signals.

In ants and some other social insects, chemical communication is predominant. A pheromone is a chemical substance, usually a type of glandular secretion, used

Table 2.2: Common communication modalities in biological social systems

Modality	Range	Information type
Sound	Long ^a	Advertising about food source, danger etc.
Vision	Short ^b	Private, e.g. courtship display.
Chemical	Short/long	Various messages, e.g. food location, alarm etc.
Tactile	Short	Qualitative info, e.g. quality of flower, peer identification etc.
Electric	Short/long	Mostly advertising types, e.g. aggression messages.

^a Depending on the type of species, long range signals can reach from a few metres to several kilometres.

^b Short range typically covers from few mm to about a metre or so.

for communication within species (Holldobler and Wilson 1990). One individual releases it as a signal and others respond to it after tasting or smelling. Using pheromones individuals can code quite complicated messages in smells. For example, a typical ant colony operates with somewhere between 10 and 20 kinds of signals. Most of these are chemical in nature. If wind and other conditions are favourable, this type of signals emitted by such a tiny species can be detected from several kilometres away.



(a) Flashing fireflies



(b) A firefly emitting light

Figure 2.12: (a) Flashing lights of fireflies displaying their synchronous behaviours (b) A firefly can produce light to signal other fireflies.

From <http://www.letsjapan.markmode.com>, last seen on 01/06/2010.

Chemical signals are extremely economical of their production and transmission. But they are quite slow to diffuse away. But ants and other social insects manage to create sequential and compound messages either by a graded reaction of different concentrations of same substance or by blends of signals. Fig.2.12

shows the social communication of fireflies by synchronous light signals.

Tactile communication is also widely observed in ants and other species typically by using their body antennae and forelegs. It is observed that in ants touch is primarily used for receiving information rather than informing something. It is usually found as an invitation behaviour in worker recruitment process. When an ant intends to recruit a nest-mate for foraging or other tasks it runs towards a nest-mate and beats its body very lightly with antennae and forelegs. The recruiter then runs to a recently laid pheromone trail or lays a new one. In this form of communication limited amount of information is exchanged. In underwater environment some fishes and other species also communicate through electric signals where their nerves and muscles work as batteries. They use continuous or intermittent pulses with different frequencies to learn about environment and to convey their identity and aggression messages.

2.2.2 Signal active space and locality

The concept of active space (AS) is widely used to describe the propagation of signals by species. In a network environment of signal emitters and receivers, active space is defined as the area encompassed by the signal during the course of transmission (McGregor and Peake 2000). In case of long-range signals, or even in case of short-range signals, this area include several individuals where their social grouping allows them to stay in cohesion. The concept of active space is described somewhat differently in the case of some social insects. In the case of ants, this active space is defined as a zone within which the concentration of pheromone (or any other behaviourally active chemical substance) is at or above threshold concentration (Holldobler and Wilson 1990). Mathematically this is denoted by a ratio:

$$AS = \frac{\text{Amount of pheromone emitted } (Q)}{\text{Threshold concentration at which the receiving ant responds } (K)} \quad (2.1)$$

Here, Q is measured in number of molecules released in a burst or in per unit of time whereas K is measured in molecules per unit of volume.

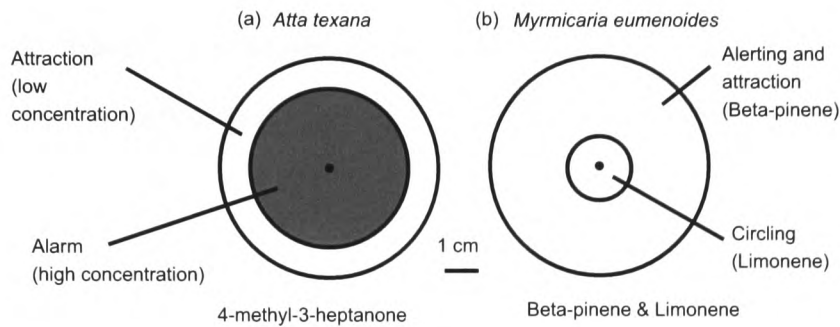


Figure 2.13: Pheromone active space observed in ants, reproduced from Holldobler and Wilson (1990).

Fig. 2.13 shows the use of active spaces of two species of ants: (a) *Atta texana* and (b) *Myrmicaria eumenoides*. The former one uses two different concentrations of 4-methyl-3-heptanone to create attraction and alarm signals, whereas the latter one uses two different chemicals: *Beta-pinene* and *Limonene* to create similar kinds of signals, i.e. alerting and circling.

The adjustment of this ratio enables individuals to gain a shorter fade-out time and permits signals to be more sharply pinpointed in time and space by the receivers. In order to transmit the location of the animal in the signal, the rate of information transfer can be increased by either lowering the rate of emission of Q or by increasing K, or both. For alarm and trail systems a lower value of this ratio is used. Thus, according to need, individuals regulate their active space by making it large or small, or by reaching their maximum radius quickly or slowly, or by enduring briefly or for a long period of time. For example, in case of alarm, recruitment and sexual communication signals where encoding the location of an individual is needed, the information in each signal increases as the logarithm of the square of distance over which the signal travels. From the precise study of pheromones it has been found that active space of alarm signal consists of a concentric pair of hemispheres (Fig. 2.13). As an ant enters the outer zone, she is attracted inward toward the point source; when she next crosses into the central hemisphere she becomes alarmed. It is also observed that ants can release pheromones with different active spaces.

Active space has strong role in modulating the behaviours of ants. For example, when workers of *Acanthomyops claviger* ants produce alarm signal due to an

Table 2.3: Common communication strategies in biological social systems

Communication strategy	Common modalities used
Indirect	Chemical and electric
P2P	Vision and tactile
Local broadcast	Sound, chemical and vision
Global broadcast	Sound, chemical and electric

attack by a rival or insect predator, workers sitting a few millimetres away begin to react within seconds. However, those ants sitting a few centimetres away take a minute or longer to react. In many cases, ants and other social insects exhibit modulatory communication within their active space where many individuals involve in many different tasks. For example, while retrieving the large prey, workers of *Aphaenogaster* ants produce chirping sounds (known as *stridulate*) along with releasing poison gland pheromones. These sounds attract more workers and keep them within the vicinity of the dead prey to protect it from their competitors. This communication amplification behaviour can increase the active space to a maximum distance of 2 meters.

2.2.3 Common communication strategies

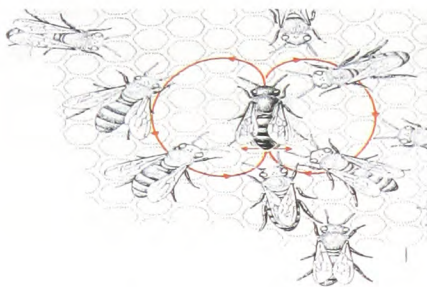
In biological social systems, many different kinds of communication strategies can be observed. They may include indirect pheromone trail laying to local and global broadcast of various signals. Sec. 2.1.2 discusses the most common four communication strategies in natural and artificial world, i.e. indirect, P2P, local and global broadcast communication strategies. Table 2.3 lists the use of various communication modalities under different communication strategies. Here a few real examples of those strategies from biological social systems have been given.



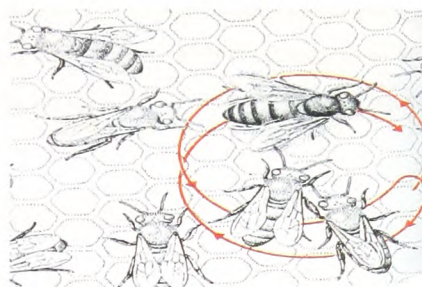
Figure 2.14: A group of ants following pheromone-trail.
From <http://www.bioteams.com>, last seen on 01/06/2010.



Figure 2.15: A dancing honey-bee (*centre*) and its followers.
From <http://knol.google.com>, last seen on 01/06/2010.



(a) Honey-bee's waggle dance



(b) Honey-bee's round dance

Figure 2.16: Examples of local broadcast communication of honey-bees: (a) Honey-bees show waggle-dance (making figure of 8) when food is far and (b) they show round-dance without any waggle when food is closer (within about 75m of hive). From Slater (1986).

In biological literature, the pheromone trail laying is one of the most discussed indirect communication strategy among various species of ants. Fig. 2.14 shows a pheromone trail following of a group of foraging ants. This indirect communication strategy effectively helps ants to find a better food source among multiple sources, find shorter distance to a food source, marking nest site and move there etc. (Hughes 2008). Local broadcast communication with nearby peers and direct P2P communication strategy is also very common among most of the biological species. For example, Fig. 2.15 shows the local broadcast communication among honey-bees and and Fig. 2.16 illustrates this strategy with two distinct types of honey-bee dances.

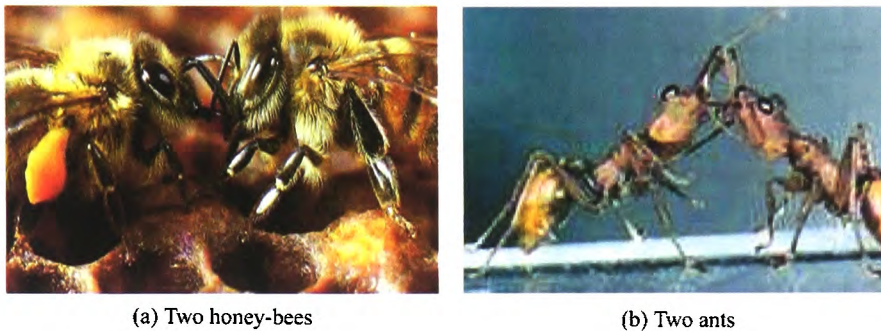


Figure 2.17: Example of P2P tactile communication: (a) Honey-bees exchange nectar samples by close contact (b) ants also exchange food or information via tactile communication. From <http://www.harunyahya.com/> last seen 01/05/2010.

Similarly, Fig. 2.17 shows the P2P communication of both honey-bees and ants. This tactile form of communication is very effective to exchange food item, flower nectar with each-other or this can be useful even in recruiting nest-mates to a new food source or nest-site.

2.2.4 Roles of communication in task-allocation

Communication among nest-mates and sensing of tasks are the integral parts of the self-regulated DOL process in biological social systems. They create necessary preconditions for switching from one task to another or to attend dynamic urgent tasks. Suitable communication strategies favour individuals to select better tasks. For example, Garnier et al. (2007) reported two worker-recruitment experiments on black garden ants and honey-bees. The scout ants of *Lasius niger* recruit uninformed ants to food source using a well-laid pheromone trails. *Apis mellifera* honey-bees also recruit nest-mates to newly discovered distant flower sources through waggle-dances. In the experiments, poor food sources were given first to both ants and honey-bees. After some time, rich food sources were introduced to them. It was found that only honey-bees were able to switch from poor source to a rich source using their sophisticated dance communication.

Table 2.4 presents the link between sensing the task and self-regulation of communication behaviours among ants and honey-bees. Here, it is seen that communication is modulated based on the perception of task-urgency irrespective of the communication strategy of a particular species. Under indirect communication

Table 2.4: Self-regulation of communication behaviours in biological social systems

Example event	Strategy	Modulation of communication upon sensing tasks
Ant's alarm signal by pheromones	Global broadcast	High concentration of pheromones increase aggressive alarm-behaviours
Honey-bee's round dance	Local broadcast	High quality of nectar source increases dancing and foraging bees
Ant's tandem run for nest selection	P2P	High quality of nest increases traffic flow
Ant's pheromone trail-laying to food sources	Indirect	Food source located at shorter distance gets higher priority as less pheromone evaporates and more ants join

strategy of ants, i.e. pheromone trail-laying, it is seen that the principles of self-organization, e.g. positive and negative feedbacks take place due to the presence of different amounts of pheromone for different time periods. Initially, food source located at shorter distance gets relatively more ants as the ants take less time to return to the nest. So, more pheromone deposits can be found in this path as a result of positive feedback process. Thus, the density of pheromones or the strength of indirect communication link reinforces ants to follow this particular trail.

Similarly, perception of task-urgency influences the P2P and broadcast communication strategies. *Leptothorax albipennis* ant take less time in assessing a relatively better nest site and quickly return home to recruit its nest-mates (Pratt et al. 2002). Here, the quality of nest directly influences its intent to make more “tandem-runs” or to do tactile communication with nest-mates. The influences of the quality of flower sources to honey-bee dance have already been discussed.

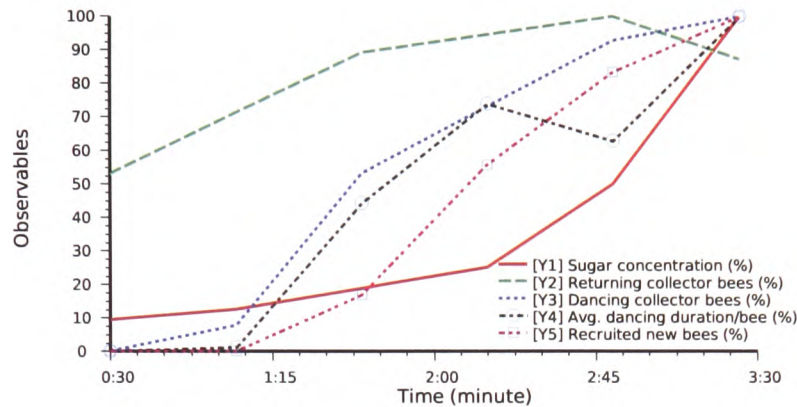


Figure 2.18: Self-regulation in honey-bee's dance communication behaviours, produced after the results of Von Frisch's (1967) honey-bee round-dance experiment performed on 24 August 1962.

Fig. 2.18 shows this phenomena more vividly. It has been plotted using the data from the honey-bee round-dance experiments of Von Frisch (1967, p. 45). In this plot, Y1 line refers to the concentration of sugar solution. This solution was kept in a bowl to attract honey-bees and the amount of this solution was varied from $\frac{3}{16}M$ to $2M$ (taken as 100%). In this experiment, the variation of this control parameter influenced honey-bees' communication behaviours while producing an excellent self-regulated DOL.

In Fig. 2.18 Y2 line represents the number of collector bees that return home. The total number of collectors was 55 (taken as 100%). Y3 line plots the percent of collectors displaying round dances. It is seen that the fraction of dancing collectors is directly proportional to the concentration of sugar solution or the sensing of task-urgency. Similarly, the average duration of dance per bee is plotted in Y4 line. The maximum dancing period was 23.8s (taken as 100%). Finally, from Y5 line it is seen that the outcome of the round-dance communication as the number of newly recruited bees to the feeding place. The maximum number of recruited bees was 18 (taken as 100%). So, from an overall observation, it can be seen that bees sense the concentration of food-source as the task-urgency and they self-regulate their round-dance communication behaviour according to their perception of this task-urgency. Thus, this self-regulated dancing behaviour of honey-bees attracts an optimal number of inactive bees to work.

Broadcast communication is one of the classic ways to handle dynamic and

urgent tasks in biological social systems. It can be commonly observed in birds, ants, bees and many other species. Table 2.4 mentions about the alarm communication of ants. Similar to the honey-bee's dance communication, ants have a rich language of chemical communication that can produce words through blending of different glandular secretions in different concentrations. Fig. 2.13 shows how ants can use different concentrations of chemicals to make different stimulus for other ants. From the study of ants, it is clear that taking defensive actions, upon sensing a danger, is one of the highest-priority tasks in an ant colony. Thus, for a highly urgent task, ants almost always use their global broadcast communication strategy through their strong chemical signals and they make sure all individuals can hear about this task. This gives a coherent picture of the self-regulation of biological species based on their perception of task-urgency.

2.2.5 Effect of group size on communication



(a) *Polistes* wasps



(b) *Polybia* wasps

Figure 2.19: Colony founding in two types of social wasps (a) *Polistes* founds colony by a few queens independently (b) *Polybia occidentalis* founds colony by swarms. From <http://www.discoverlife.org>, last seen 01/05/2010.

The performance of cooperative tasks in large group of individuals also depends on the communication and sensing strategies adopted by the group. As introduced in Sec. 1.2, from the study of social wasps, it is found that depending on the group size, different kinds of information flow occur in different types of social wasps (Jeanne 1999). *Polistes* independent founders are species in which reproductive females establish colonies alone or in small groups with about 10^2 individuals at maturity (Fig. 2.19(a)). *Polybia* swarm founders (Fig. 2.19(b)) initiate colonies by swarm of workers and queens. They have a large number of individuals, in the

order of 10^6 and 20% of them can be queen.

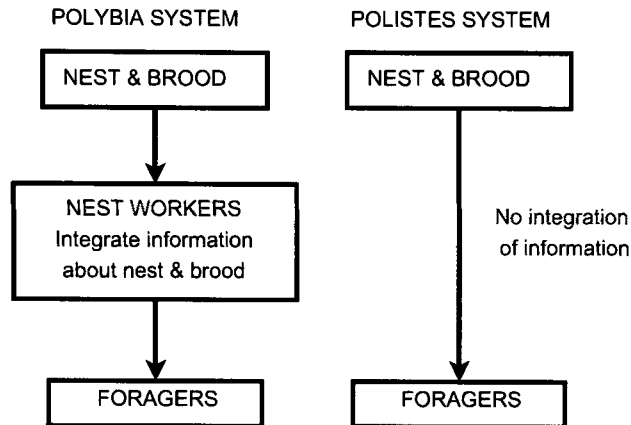


Figure 2.20: Different patterns of information flow in two types of social wasps: polybia and polistes, reproduced from Jeanne (1999).

Fig. 2.20 compares the occurrence of information flow among independent and swarm founders. In case of swarm founders information about nest-construction or broods food-demand cannot reach to foragers directly.

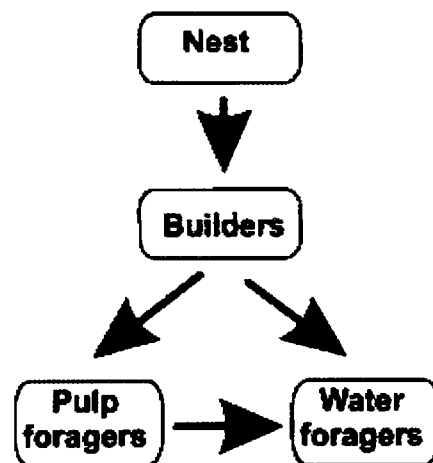


Figure 2.21: Information flow in polybia social wasps, reproduced from Jeanne (1999).

Fig. 2.21 shows the path of information flow among swarm founders for nest construction. The works of *pulp foragers* and *water foragers* depend largely on their communication with *builders*. On the other hand, in case of independent

founders there is no such communication and sensing are present among individuals. In Sec. 1.2 these two types communication and sensing strategies have been termed as GSNC (for independent founders) and LSLC (swarm founders).

Jeanne (1999) explained the above phenomena of selecting different strategies in terms of task-specialization patterns and stochastic properties found in the group. In case of large colonies, many individuals repeatedly perform same tasks as this minimizes their interferences, although they still have a little probability to select a different task randomly. But because of the large group size, the queuing delay in inter-task switching keeps this task-switching probability very low. Thus, in swarm founders, task-specialization becomes very high among individuals. On the other hand, in small group of independent founders, specialization on a specific task is very costly, because this prevents individuals not to do other tasks whose task-urgencies can soon become very high. Thus these individuals tend to become generalist and do not communicate task information with each other.

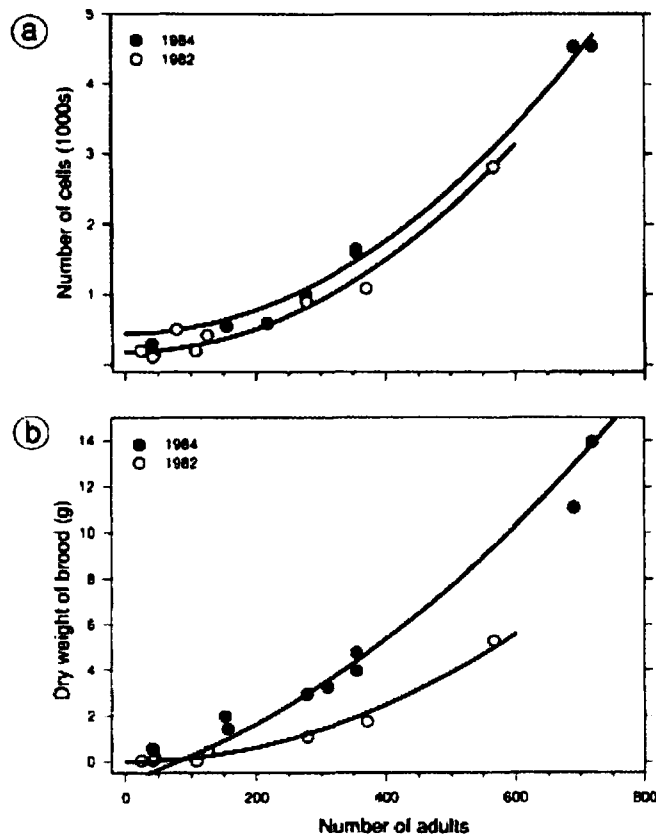


Figure 2.22: Productivity of social wasps shown as a function of group size, reproduced from Jeanne (1999).

The above interesting findings on GSNC and LSLC in social wasps have been linked up with the group productivity of wasps. Fig. 2.22 illustrates high group productivity in case of LSLC of swarm founders. The per capita productivity was measured as the number of cells built in the nest in (a) and the weight of dry brood in grams in (b). In case of independent founders this productivity is much lesser (max. 24 cells per queen at the time the first offspring observed) comparing to the thousands of cells produced by swarm founders. This shows the direct link between high productivity of social wasps and their selection of LSLC strategy. These fascinating findings from wasp colonies have motivated the author of this thesis to test these communication and sensing strategies in a fairly large multi-robot system to achieve an effective self-regulated MRTA.

2.3 Summary

This chapter reviews three relevant terms i.e. self-regulation, communication and DOL along with a detailed discussion on communication in biological social systems. The ingredients of self-organization and its link with self-regulation have been included in this general review. From the discussions of different communication modes and strategies it is clear that there is a strong relationship between the selection of communication strategies and producing efficient self-regulated DOL among biological species. Here it is also interesting to note that the concept of signal active space or communication range can be used as an effective strategy to modulate communication. In the following chapters the two distinct types of communication and sensing strategies found in social wasps, i.e. GSNC and LSLC, will be used for designing the communication experiments for self-regulated MRTA.

Robotics Background and Related Work

3.1 Overview of multi-robot systems

3.1.1 MRS research paradigms

Historically the concept of multi-robot system comes almost after the introduction of behaviour-based robotics paradigm (Brooks 1986). In 1967, using the traditional sense-plan-act or hierarchical approach (Murphy 2000), the first artificially intelligent robot, Shakey, was created at Stanford Research Institute. In late 80s, Brooks influenced this entire field of mobile robotics by his layered behaviour-based robot-control approach that acted significantly differently than the hierarchical approach.

At the same time, Braitenberg (1984) described a set of experiments where increasingly complex vehicles could be built from simple mechanical and electrical components. Around the same time and with similar principles, Reynolds (1987) developed a distributed behavioural model for a bird in a flock that assumed that a flock is simply the result of the interactions among the individual birds (see Sec. 3.1.4). Early researches on multi-robot systems also include the concept of cellular robotic system (Fukuda and Nakagawa 1987, Beni 1988) multi-robot motion planning (Arai et al. 1989, Premvuti and Yuta 1990, Wang 1989) and architectures for multi-robot cooperation (Asama et al. 1989).



Figure 3.1: The Nerd-Herd. From Mataric (1994)



Figure 3.2: A group of 10 box pushing robots. From Kube (1997)

Fig. 3.1 and 3.2 present the two earliest multi-robot systems in foraging and box-pushing task domains, developed by two pioneers in this field, Mataric (1994) and Kube (1997) respectively.



(a) Robot teams at Robocup soccer



(b) Robot team at Robocup rescue

Figure 3.3: Example of multi-robot system at sports and rescue (a) Robot dogs playing at Robocup soccer.

From <http://news.bbc.co.uk>, reported on 11/05/2005. (b) Rugbot robot team was competing at Osaka's Robocup rescue league from Birk et al. (2006).

From the beginning of the behaviour-based paradigm, the biological inspirations influenced many cooperative robotics researchers to examine the social characteristics of insects and animals and to apply them to design multi-robot systems (Arkin 1998). The underlying basic idea is to use simple local control rules of various social species, such as ants, bees, birds etc., to the development of similar behaviours in robots. In multi-robot literature, there are many examples that demonstrate the ability of multi-robot teams to aggregate, flock, forage, follow trails etc. (Bonabeau et al. 1999). The dynamics of ecosystem, such as cooperation, has also been applied in multi-robot systems that has presented the emergent

cooperation among team members (McFarland 1994, Martinoli et al. 1996).

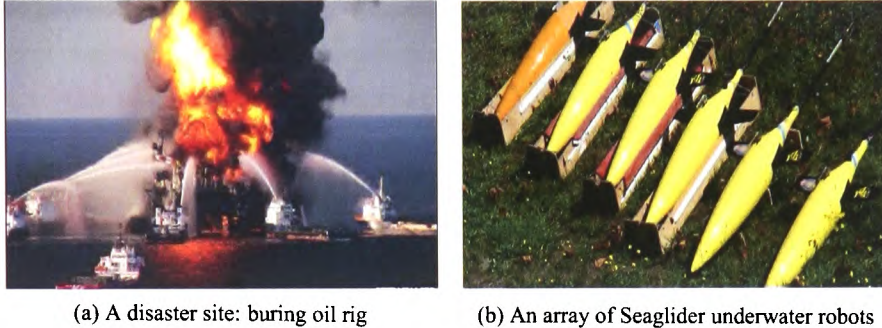


Figure 3.4: Example of multi-robot system working at a disaster site (a) British Petroleum's oil rig sinks in the Gulf of Mexico after explosion. From <http://news.bbc.co.uk>, reported on 22/04/2010. (b) IRobot's Seaglider fleet that was surveying oil spill in the Gulf of Mexico at depths of up to 1,000 meters. From <http://www.irobot.com>, reported on 25/05/2010.

On the other hand, the study of competitive behaviours among animal and human societies has also been applied in multi-robot systems, such as in multi-robot soccer (Asada et al. 1999). Fig. 3.4 and 3.3 show that multi-robot system can be used to develop a wide range of useful applications ranging from human disaster recovery to games and entertainment.

As discussed above, there are several research groups who follow different approaches to handle multi-robot research problems. Based on the underlying philosophies and principles, they are classified into two broad paradigms: i) traditional multi-robot system and ii) swarm robotic system. Below they are briefly highlighted and Sec. 3.1.3 and 3.1.4 present and review of various issues of these systems.

1. Traditional multi-robot system paradigm

Traditional multi-robot systems follow the organizational, social, knowledge-based and multi-agent based approaches to solve problems of multi-robot system. They do not take inspiration from biological social systems directly. Explicit modelling of environment, tasks, robots can be the main features of these systems. Traditional multi-robot systems can be classified into the following two broad categories (Parker 2008).

A. Organizational and social approaches: Organizational and social paradigms

are typically based on organization theory derived from human systems that reflect the knowledge from sociology, economics, psychology and other related fields. To solve complex problems this paradigm usually follows the cooperative and collaborative forms of distributed intelligence. In multi-robot systems the example of this paradigm is found in two major formats: 1) the use of roles and value system and 2) market economics. For example, in multi-robot soccer (Stone and Veloso 1999) positions played by different robots are usually considered as defined roles. Market economics approach (Dias et al. 2006) uses market economics theory that enables the selection of robots for specific tasks according to their individual capabilities determined by a bidding process.

B. Knowledge-based and multi-agent based approaches: This paradigm, commonly used for developing multi-agent systems, is knowledge-based, ontological and semantic paradigm. Here knowledge is defined as ontology and shared among robots/agents from disparate sources. It reduces the communication overhead by utilizing the shared vocabulary and semantics. Due to low bandwidth, limited power, limited computation, noise and uncertainty in sensing/actuation, the use of this approach is usually restricted in multi-robot systems.

2. Swarm robotic paradigm

In bio-inspired, emergent swarm robotic paradigm, local sensing and local interaction form the basis of collective behaviours of swarms of robots. Today, this paradigm has been emerged as a sub-field of robotics called *swarm robotics* (Sahin and Spears 2005). This is a powerful paradigm for those applications that require performing shared common tasks over distributed workspace, redundancy or fault-tolerance without any complex interaction of entities. Some examples include flocking, herding, searching, chaining, formations, harvesting, deployment, coverage etc.

Although the approximate classification of multi-robot system includes most of the research directions, it is very hard to specifically categorize all diverse researches on multi-robot systems. However, most of the researchers select a suitable paradigm to abstract the problem from a specific perspective with common fundamental challenges of multi-robot system discussed in the later sections.

3.1.2 MRS taxonomies

The vast amount of research in multi-robot system makes it necessary to use well-established classifications or taxonomies in order to specify and design a useful multi-robot system. In Section 3.1.1 the main-stream research in multi-robot system has been classified into two distinct paradigms. However, these paradigms have certain assumptions, often unspecified or implicit, regarding the design of robot hardware, software, communication and interaction etc. Thus, multi-robot system taxonomies can be useful for many purposes, e.g. to avoid ambiguities in system specification by reducing the size and complexity of possible design spaces, and to use certain trade-off among various features for achieving overall system performance.

While earlier multi-robot system taxonomies, e.g. one proposed by Premvuti and Yuta (1990), Cao et al. (1997) discuss very fundamental design issues of multi-robot system, recent taxonomies e.g. proposed by Dudek et al. (2002), Gerkey and Mataric (2004), Balch (2002), Farinelli et al. (2004) etc. give the detail design choices for making useful system specifications. These recent taxonomies have been classified into two groups: 1) generalized taxonomies and 2) specialized taxonomies. In this thesis, the taxonomies of Dudek et al. (2002) and Parker (2008) have been used as generalized taxonomies since they can be used to specify almost all necessary features of a multi-robot system.

On the other hand, specialized taxonomies provide multi-robot system specification with respect to particular system features, e.g., the taxonomy of Balch (2002) is only useful in a multi-robot system with reinforcement learning, the taxonomy of Gerkey and Mataric (2004) gives the specification of tasks in a MRTA context. Other less common taxonomies e.g., one proposed by Farinelli et al. (2004) or another proposed by Cao et al. (1997) are centred around the coordination (weak, strong or none), communication (implicit, explicit or none), architecture (centralized or decentralized) etc. Here the major axes of leading taxonomies of multi-robot systems have been described.

Generalized taxonomy of multi-robot systems

The generalized taxonomy of Dudek et al. (2002) provides seven main axes for multi-robot team specification. They are regrouped into the following three areas.

1. Collective or group size, composition and reconfigurability: A multi-robot system can be formed by one, two, multiple or virtually infinite number of autonomous robots. Composition refers to the homogeneity of the group members. Robots can be identical in both form and function (hardware and software), homogeneous (consisting of same physical hardware) or physically heterogeneous. Collective reconfigurability refers to the rate at which robots can spatially re-position themselves. It can be completely static, coordinated or dynamically arranged.

2. Communication range, topology and bandwidth: The maximum distance between two robots, required for effective communication, can be zero (i.e. they cannot communicate directly) or infinite (i.e. all robots can communicate to any other robot) or in-between these two options. Communication topology determines the style of addressing target peers e.g., through broadcast messaging, individual addressing by name or address or, following tree-like hierarchy or redundant graphs. Communication bandwidth provides the measure of costs associated with communication. This can be no cost (i.e. infinite bandwidth) or high cost (i.e. limited or no bandwidth) or something in between these two extreme cases.

3. Processing abilities: This refers to the software architectures that can be used for deploying controllers of robots. General models include finite state automata, a push-down automata, neural-networks or Turing machines.

Specialized taxonomies of multi-robot systems

The taxonomy of Gerkey and Mataric (2004) defines three axes of possible tasks and robot capabilities of multi-robot system:

- 1. Single-task robots vs. multi-task robots:** The former (latter) means a robot can perform one (multiple) task at a time.
- 2. Single-robot tasks vs. multi-robot tasks :** while under the former, each task requires only one robot, under the latter, multi-robots may be required.
- 3. Instantaneous assignment vs. time-extended assignment :** While the former refers a situation when planning for future task-allocations is not possible, under latter, planning is possible.

Balch (2002) extended this taxonomy of tasks and applied to multi-robot learning cases. His taxonomy of reward include: source of reward (internal or external or both), rewarding time (immediate or delayed), continuity of reward (discrete or

continuous), locality of reward (global or local or a combination of both) relation to performance (tied to performance or based-on intuitive state-value).

Taxonomy of interaction in multi-robot teams

In addition to the above two classes of taxonomies, here Parker's (2008) notion of *interaction* in a robot team has been described in four levels: 1) collective, 2) cooperative 3) collaborative and 4) coordinative.

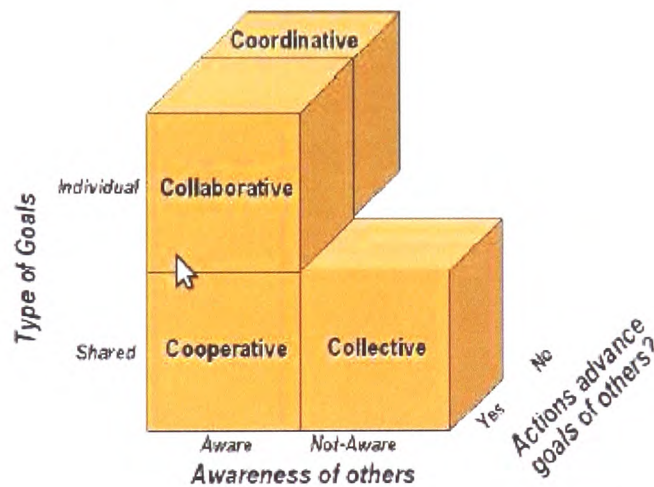


Figure 3.5: Categorization of types of interactions in multi-robot system, reproduced from Parker (2008).

As seen in Fig. 3.5, the interactions among a multi-robot team can be viewed along three different axes:

1. Types of goals of entities: either shared goal such as, cleaning a floor, or, individual goal.
2. Awareness of entities about others on the team: either aware such as, in cooperative transport, or, unaware such as, in a typical foraging.
3. Influence of the action of one entity to advance the goal of others: such as, one robot's floor cleaning helps other robots not to clean that part of the floor.

Based on this axes interaction can be classified into four categories:

1. **Collective interaction:** Entities are not aware of others on the team, yet do

share goals and their actions are beneficial to team-mates. Most swarm-robotic systems follow this kind of interaction to perform biologically-relevant tasks, such as foraging, swarming, formation keeping and so forth.

2. Cooperative interaction: Entities are aware of others on the team, they share goals and their actions are beneficial to their team-mates. This type of interaction is used to reason about team-mates' capabilities where multiple robots work together, usually in a common shared workspace, such as cleaning a work-site, pushing a box, performing search and rescue, extra-planetary exploration and so forth.

3. Collaborative interaction: Having individual goals (and even individual capabilities), entities aware of their team-mates and their actions are beneficial to their team-mates. One example of this kind of interaction is a team of collaborative robots where each must reach a unique goal position by sharing the sensory capabilities to all members such as found in coalition formation (Parker and Tang 2006).

4. Coordinative interaction: Entities are aware of each other, but they do not share a common goal and their actions are not helpful to other team members. For example, in a common workspace, robots try to minimize interference by coordinating their actions as found in multi-robot path planning techniques, traffic control techniques and so on.

Beyond this four most common types of interactions another kind of interaction can be found in adversarial domain where entities effectively work against each other such as multi-robot soccer. Here entities have individual goals, they are aware of each other, but their actions have a negative affect on other robots' goals. Most researches do not consider these type team as a typical swarm robotic system which is explained later.

In this dissertation, the taxonomy of Dudek et al. (2002) has been used for specifying a multi-robot system (Sec. 4.1.2). The taxonomy of Parker (2008) is used to analyse the dependence of multi-robot system on various levels of interactions in Sec. 3.2.



Figure 3.6: Hundreds of Centibots robots worked at indoor search, navigation and mapping tasks. From Ortiz et al. (2005).



Figure 3.7: Pioneer robots operating at outdoor uncertain environment of Georgia Tech. Mobile Robot Lab. From <http://news.cnet.com>, reported on 05/04/2010.

3.1.3 Traditional MRS

Multi-robot systems not only share the problem of controlling a single robot but also amplify the problem to several orders of magnitude, for example in case of hundreds of Centibots robots as shown in Fig. 3.6. Below a few major challenges of any multi-robot system are listed:

- **Increased uncertainty about environment:** When multiple robots work in a partially observable world, the environmental view becomes severely restricted due to both in terms of noisy sensor readings and frequent obstacle detections. Thus, in multi-robot system, the uncertainty about the environment increased in many folds (an example is shown in Fig. 3.7).
- **Increased dynamic changes of the environment:** Since many robots work in a shared environment, the dynamic movements and physical interferences among the robots become more frequent. So robots are required to change their course of action more frequently.
- **Decreased communication throughput:** Interference in communication is inescapable for a team of robots. Since the typical bandwidth of a communication channel is fixed, adding more robots reduces the effective communication throughout and thus increased latency in robot-robot or robot-computer communications. If the robots are required to coordinate their ac-

tion then saturation of the communication channel affects the overall team-performance.

- **Decreased real-time performance:** In a functional multi-robot system, autonomous mobile robots need to do some tasks in real-time, e.g. identifying their current poses (*localization*) to determine next motions, avoiding obstacles etc. However, when the number of robots increases the real-time performance can be poor due to the above factors.
- **Increased sensor failures and break-downs:** This is also common in a multi-robot system that the real-time interaction of large number of robots can decrease the life of their hardware as they become subject to more collisions and interferences. Thus overall reliability of the multi-robot system can be decreased gradually.

Despite the above big challenges, researchers design and operate multi-robot system successfully using a number of intelligent solutions since the last few decades. In the previous subsections it is shown how the researches are classified into distinctive paradigms and they are specified by precise taxonomies. Here a number of typical issues have been listed which any multi-robot system typically encounters from its inception to implementation.

- *Motion control.* How to use sensor values to produce real-time motions avoiding obstacles?
- *Localization.* How to find out self-position in the world so that reaching to a specified target location becomes possible?
- *Navigation/map-building.* How to integrate sensor values to build maps or representation of the environment for further exploration?
- *Task-selection.* How to plan/predict and select a particular high-level task (e.g. find a red object or pick up a stick) provided that a number of tasks are present in the environment?
- *Interaction and communication.* How to interact or communicate with other robots for cooperating, collaborating or coordination in doing tasks?

- *Adaptation/learning.* How to remember things so that future robot actions or behaviours become improved?

Not all of the above issues are present in all multi-robot systems. Many multi-robot systems do not use any form of navigation, communication or learning and yet they do some useful tasks. However it is important to understand how these issues can be solved in a structured, modular and timely manner. For example, conflicts occur if a resource is required by or, a unique single task is distributed to, more than one robot at any given time. Several resources such as bandwidth, space etc. may be needed by more than one robot. The sharing of bandwidth among robots is a great problem in case of applications like multi-robot mapping (Konolige et al. 2003). As shown in Fig. 3.6, in a large multi-robot team such as in Centibots system (Ortiz et al. 2005), task interference and high bandwidth communication between 100s of robots appear as a significant research challenge.

Whatever be the principle characteristics of a multi-robot system, e.g., homogeneity, coupling, communication methods etc., each multi-robot system must address to some degree to those problems. For example, usually every multi-robot system adopts a control architecture under a specific paradigm to organize its hardware, software and communication system. Similarly every multi-robot system address the issues of communication, localization, interaction in a way specific to the application and underlying design principles or philosophies. In the following subsections, the key research issues have been summarized which can potentially influence the selection and implementation of any multi-robot system.

Architecture and control

In multi-robot system, two high-level control strategies are very common: 1) centralized and 2) decentralized or distributed. Under a specific control strategy, traditionally three basic system architectures are widely adopted: deliberative, reactive and hybrid (Arkin 1998). Deliberative systems based on central planning are well suited for the centralized control approach. The single controller makes a plan from its *sense-plan-act* loop by gathering the sensory information and each robot performs its part.

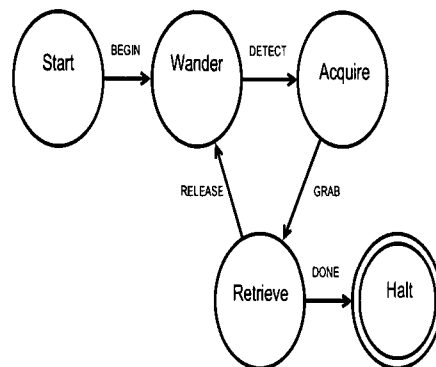


Figure 3.8: Finite state machine for foraging task, reproduced from Arkin (1998).

Reactive systems are widely used in distributed control where each robot executes its own controller maintaining a tight coupling between the system's sensors and actuators, usually through a set of well-designed behaviours. A finite state machine describing the behaviours of foraging tasks is shown in Fig. 3.8. Here, various group behaviour emerges from the interactions of individuals that communicate and cooperate when needed.

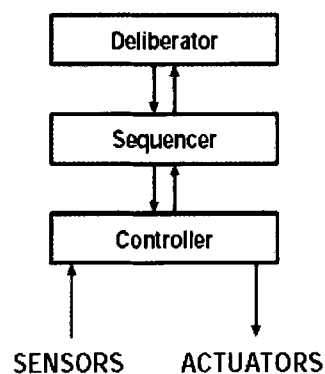


Figure 3.9: A typical hybrid robot control architecture, adopted from Mataric (2007).

As shown in Fig. 3.9, hybrid systems are usually the mixture of the two above approaches; where each robot can run its own hybrid controller with the help of a plan with necessary information from all other robots. Behaviour-based control

architecture can also be considered as a separate category of distributed control architecture, where each robot behaves according to a behaviour-based controller and can learn, adapt and contribute to improve and optimize the group-level behaviour (Mataric 2007). Although most of the multi-robot system control architectures share some common characteristics (such as distributed and behaviour-based control strategy) based on their difference of underlying design principles they have been put into three groups:

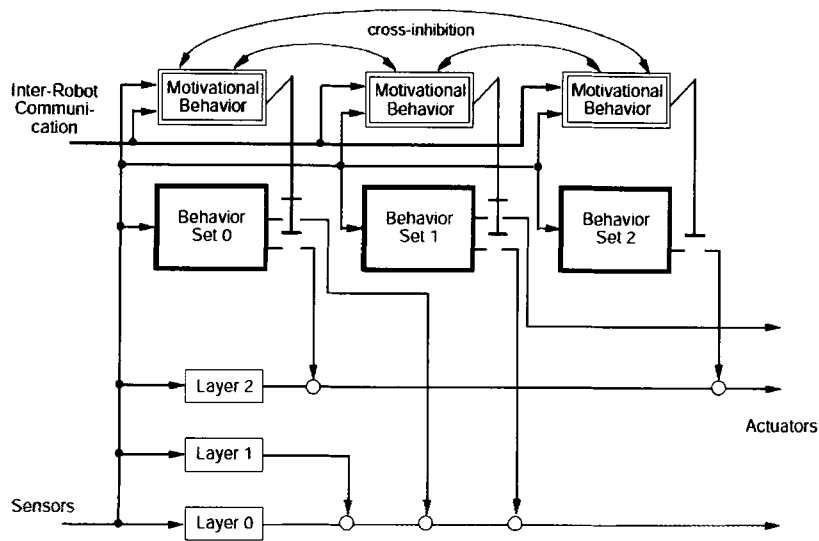


Figure 3.10: ALLIANCE architecture. From Parker (1998).

1. **Behaviour-based classical architectures:** The ALLIANCE architecture (Parker 1998) is one of the earliest behaviour-based fully distributed architectures (Fig. 3.10). This architecture has used the mathematically modelled behaviour sets and motivational system. The primary mechanism for task selection of a robot is to activate the motivational behaviour partly based on the estimates of other robots behaviour. This architecture was designed for heterogeneous teams of robots performing loosely coupled tasks with fault-tolerance and co-operative control strategy. Broadcast of local eligibility (Werger and Mataric 2001) is another behaviour-based architecture that uses port-attributed behaviour technique through broadcast communication method. It was demonstrated to perform coordinated tasks, such as multi-

target observation tasks. Similar to the above two architectures, many other researchers proposed and implemented many variants of behaviour-based architectures. Some of them used the classic three layer (plan-sequence-execute) approach, (Simmons et al. 2002) used a *layered architecture*.

2. **Market-based architectures:** Using the theory of market economics and well-known Contract Net Protocol (Davis and Smith 1988), these architectures solve the task-allocation problem by auction or bidding process. Major architectures following market-based approaches include MURDOCH (Gerkey and Mataric 2002), M+ system (Botelho et al. 1999), first-piece auction (Zlot et al. 2002), dynamic role assignments (Chaimowicz et al. 2002) among others.
3. **Multi-agent based architectures:** Some multi-robot system architectures are influenced by multi-agent systems. For example, CHARON is a hierarchical behaviour-based architecture that rely on the notion of agents and modes (Chaimowicz et al. 2002). Similarly CAMPOUT is another distributed behaviour-based architecture that provides high-level functionality by making use of basic low-level behaviours in downward task decomposition of a multi-agent planner (Huntsberger et al. 2003). It is comprised of five different architectural mechanisms including, behaviour representation, behaviour composition, behaviour coordination, group coordination and communication behaviours.

In this dissertation, the behaviour-based hybrid architecture has closely been followed with an event-driven mechanism for activating behaviours. The multi-robot control architecture and robot controllers used in this thesis are illustrated in Sec. 4.3.

Learning

A great deal of research on multi-robot learning has been carried out since the inception of multi-robot system (Mataric 2001, Parker 1995). Learning, identified as the ability to acquire new knowledge or skills and improve one's performance, is useful in multi-robot system due to the necessity of robot to know about itself, its

environment and other team-members (Mataric 2007). Learning can improve performance since robot controllers are not perfect by design and robots are required to work in an uncertain environment where all possible states or actions cannot be predicted in advance. Besides learning, it is also important to forget learned things that are no longer needed (or correct) as well as to make room for new things to be learned and stored in a finite memory space of a robot.

Several learning techniques are available in robotics domain, such as reinforcement or unsupervised learning, supervised learning and learning by imitation. Although reinforcement learning, or learning based on environmental or peer feedback, is a good option for multi-robot system, it has been found that in large teams the ability to learn in this way is restricted due to large continuous state and action space (Yang and Gu 2004). Several other learning techniques are also available to explore in multi-robot system domain including Markov models, Q-learning, fuzzy logic, neural nets, game theory, probabilistic or Bayesian theory among others.

Localization and exploration

Mobile robot systems highly rely on precise localization for performing their autonomous activities in indoor or outdoor. Localization is the determination of exact pose (position and orientation) with respect to some relative or absolute coordinate system. This can be done by using proprioceptive sensors that monitor motion of a robot or exteroceptive sensors that provide information of world representation, such as global positioning system (GPS) or indoor navigation system. Many other methods are also available, such as landmark recognition, cooperative positioning and other visual methods (Arkin and Diaz 2002).

Localization issue of multi-robot system also invites researchers to examine specific areas like exploration and map generation. In exploration problem, robots need to minimize the time needed to explore the given area. Many researchers use various kinds of exploration algorithms for solving this NP-hard problem, such as line-of-sight constrained exploration algorithm, collaborative multi-robot exploration (Burgard et al. 2000). In mapping problem, mostly inaccurate localization information from teams of robots are accumulated and combined to generate a map by various techniques, such as probabilistic approaches (Thrun et al. 2000).

Example research areas of multi-robot system

Researches on multi-robot system have been targeted for numerous application domains that all cannot be listed here. Here a few major areas have been included that have received highest attention in the robotics research community.

Cooperative transport of large objects by multiple robots was investigated by many researchers such as, following a formal model of cooperative transport in ants (Kube and Zhang 1993), box-pushing by six-legged robots (Mataric et al. 1995). Another kind of object transport problem include clustering objects into piles (Beckers et al. 1994), collecting waste or trash (Parker 1994), sorting coloured objects (Melhuish et al. 1998) and so on. It has also been observed that multi-robot teams as micro or mini machines are helpful to improve the control and efficiency of mining and its processing operations (Dunbar and Klein 2002).

Many researchers address research issues under the requirements of a military or space application, e.g. behaviour-based formation control (Balch and Arkin 1998), landmine detection (Franklin et al. 1995), multiple planetary rovers for various missions (Huntsberger et al. 2004).

Although research on multi-robot system has been becoming more mature since last decades, it is not easy to find many industrial applications relying on multiple autonomous mobile robots. One exceptional application has been developed by Kiva Systems in the domain of multi-robot material handling in warehouses (Wurman et al. 2008). Along with this, Sec. 3.4 reviews some possible applications of multi-robot system in automation industry.

3.1.4 Swarm robotic system

When many traditional multi-robot systems showed serious scalability failures, the necessity of adopting a new paradigm became obvious (Lerman et al. 2006). Researchers of traditional multi-robot system approach realized that executing their time and processing intensive algorithms in large number of real robots (≥ 10) could be a nightmare. Adding more robots almost exponentially amplified their inherent problems e.g. physical and communication interferences with an ever-ending hunger of more CPU powers.

In early and mid-90s, many researchers found that applying biological principles of swarm intelligence effectively removed and reduced many bottlenecks

of traditional multi-robot system. In 1995, Maja Mataric published that complex group behaviours could be produced by the appropriate combinations of more simple “basis behaviours” (Mataric 1995). The idea of using simple biological behaviours, such as avoidance and following, to create complex flocking and foraging behaviours inspired many other researchers to search solution for controlling large multi-robot system in this direction. The early research of Reynold (1987) helped many others to apply the principles of swarm intelligence in multi-robot system.

The term *swarm intelligence* was first coined by Beni (1988). It represents the effort of designing distributed problem solving algorithms inspired by the collective behaviours of social insect colonies (Bonabeau et al. 1999). The idea of using simple robots to create complex patterns or structures was also studied under *cellular robotics* (Fukuda and Nakagawa 1987). During recent years, *swarm robotics* has emerged as an application of swarm intelligence in multi-robot systems with the emphasis on physical embodiment of entities and realistic interactions among the entities and their environment. These systems of swarms or minimalist robots¹ can be represented by a common term *swarm robotic system*.

Advantages of swarm robotic system

The simplicity of swarm robotic system inspires researchers to build multi-robot system with cheap robotic hardware, to equip them with simple controllers and control them through local information, without creating any explicit model of the environment or using any sophisticated controller. The redundancy of robots, parallelism in their task-executions and an overall distributed control architecture, support addition or removal (or failure) of robots in run-time. Moreover the control algorithms are now decoupled from the model of the environment or other robots. Thus this system now becomes more robust, fault-tolerant, scalable and adaptive to unknown and dynamic environment.

Distinct features of swarm robotic system

In order to distinguish swarm robotics from other branches of robotics such as collective robotics, distributed robotics, robot colonies and so forth, Sahin and Spears

¹Although both swarm robotics and minimalist robotics follow similar approaches for solving similar problems, the latter does not explicitly relate its origin to swarm intelligence.

(2005) proposed a formal definition and a set of criteria for swarm robotics research.

“Swarm robotics is the study of how large number of relatively simple physically embodied agents can be designed such that a desired collective behaviour emerges from the local interactions among agents and between the agents and the environment.”

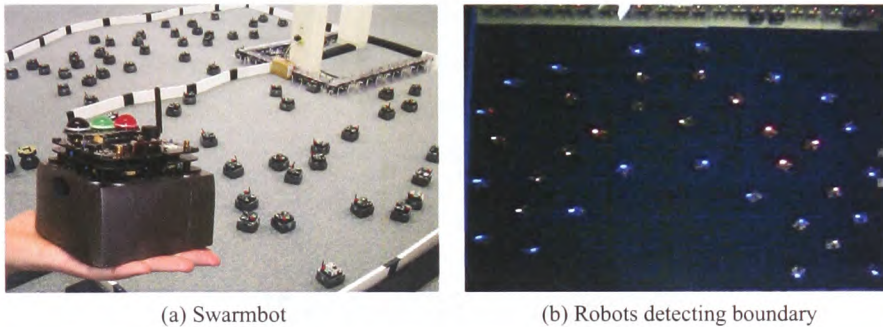


Figure 3.11: (a) A Swarmbot and the Swarms (b) Swarmbots detecting boundary using distributed algorithms, from McLurkin and Demaine (2009).

And the notable criteria of swarm robotics research are listed as follows.

1. **Autonomous robots:** that exclude the sensor networks and may include metamorphic robotic system without having no centralized planning and control element.
2. **Large number of robots:** usually ≥ 10 robots, or at least having provision for scalability if the group size is below this number. As shown in Fig. 3.11, using hundreds of robots to form a swarm robotic team is not rare now a days.
3. **Mostly homogeneous groups of robots:** that typically exclude the multi-robot soccer teams having heterogeneous robots.
4. **Relatively incapable of inefficient robots:** so that the task complexity enforces either cooperation among robots or increased performance or robustness without putting no restriction on individual robot's hardware/software complexity.

5. **Robots with local sensing and communication capabilities:** that does not use global coordination channel to coordinate among themselves, rather enforces distributed coordination.

Classification and application of swarm robotic system

Swarm robotic system can broadly be classified into two distinct classes. The first class consists of simple and relatively inexpensive mobile robots that are fully autonomous and can work in isolation. For example, e-puck robots (Cianci C. and A. 2004) fall under this class. Other class of robots include self-reconfigurable (Fukuda and Nakagawa 1987) and self-assembling robots which can be built by coupling several identical units together, e.g. a robotic snake. In this dissertation, only the former class of robots has been considered.



(a) Swarmbots at exploration



(b) Swarmbots at mock rescue

Figure 3.12: A group of Swarmbots (a) crossing a rough terrain (b) pulling a child to a safe location, from Mondada et al. (2004).

Fig. 3.12 (a) shows amazing abilities of Swarmbots which are crossing a rough terrain. Fig 3.12 (b) shows another interesting demonstrations of swarm robotic system that a team of 18 Swarmbots pulls a child to a safe place.

Modelling swarm robotic system

Modelling both the behaviour of an individual robot controller and the overall system-level collective behaviours have become interesting issues. This is due to the fact that, in this kind of system, collective behaviours, e.g. flocking or aggregation, can significantly be changed by just changing one or few parameters of individual robot controllers. Modelling swarm robotic system can give an early insight about a target system before its implementation and any time-consuming simulation or expensive real-experiment.

Plenty of approaches are available for modelling swarm robotic system (Gazi and Fidan 2007). Most common modelling approaches include: behaviour-based approach, probabilistic models, potential-function based approach, asynchronous swarm models, multi-agent based swarm models.

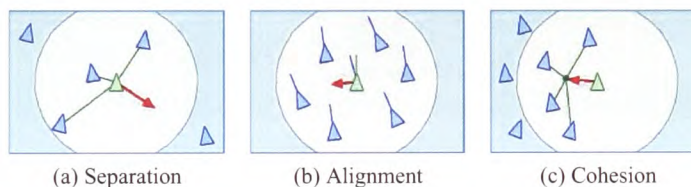
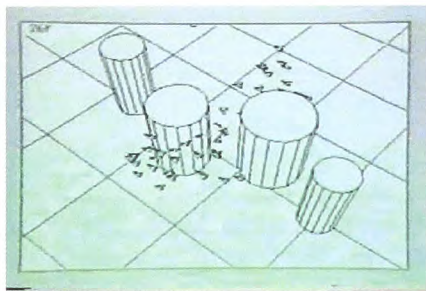


Figure 3.13: Reynold's simulated flocking of boids from Reynolds (1987). (a) Separation: steer to avoid crowding local flockmates, (b) Alignment: steer towards the average heading of local flockmates and (c) Cohesion: steer to move toward the average position of local flock-mates.

From <http://www.red3d.com/cwr/boids/>, last seen on 01/06/2010.



(a) A flock of birds

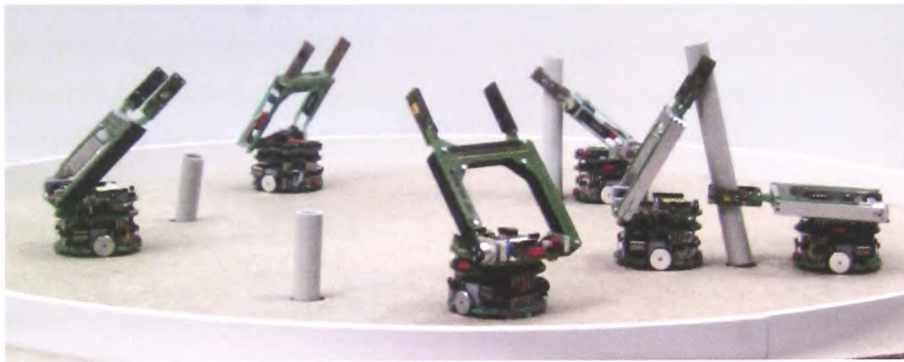


(b) Simulated boids

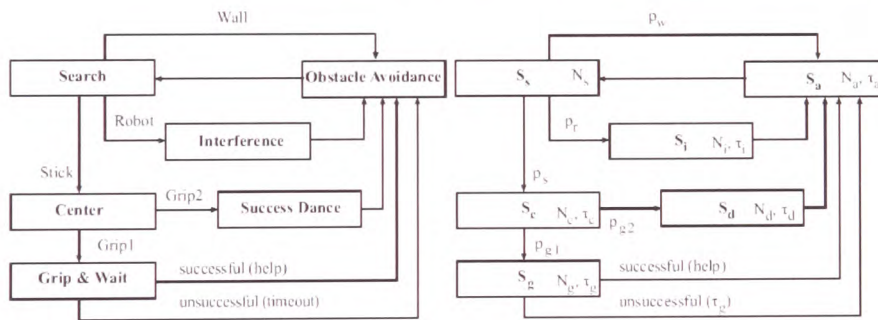
Figure 3.14: (a) Real flocks of birds, from <http://www.travelblog.org>, and (b) simulated flock of birds, from <http://www.red3d.com/cwr/boids/>, last seen on 01/06/2010.

Behaviour-based approach can be found in the study of Reynolds (1987) who

has simulated the flocking behaviours of birds. Fig. 3.13 illustrates how three simple rules can produce a coordinated flocking motion (Fig. 3.14(b)). From biological observation of flocking birds it is obvious that collective behaviours can be generated through local control and interaction rules. Similar to this study, many other researchers tried to apply behaviours based on local strategy for formation control (Balch and Arkin 1998), aggregation (Mataric 1995), sorting (Melhuish et al. 1998), foraging (Liu et al. 2007), cooperative transport (Kube 1997) etc.



(a) Robots pulling sticks



(b) Probabilistic finite state machine

Figure 3.15: (a) Stick-pulling experiments by a group of Khepera robots equipped with gripper turrets and (b) Probabilistic finite state machine (PFSM) of robot controllers.

From Agassounon et al. (2004).

In 1999, Martinoli (1999) proposed probabilistic modelling of swarm robotic system. This probabilistic approach often has two major aspects: controller design through probabilistic finite state machine (Fig. 3.15) and automated parameter adaptation through genetic algorithm. This approach has been adopted by many

recent swarm robotic researches (Agassounon et al. 2004, Lerman et al. 2005, Liu et al. 2007b).

Swarm robotic models can be classified into many distinct classes. Firstly, they can be classified into: spatial and non-spatial models. *Spatial models* keep track of the agent's trajectories and perhaps use that spatial distribution. However, in *non-spatial models* it is assumed that agents occupy independent, random positions at consecutive time-steps. Swarm robotic models can also be classified into embodied and non-embodied models. *Non-embodied models* consider agents as points and their physical characteristics are ignored, whereas *embodied models* take the physical characteristics or interferences of agents into account. Spatial models with embodied agents are chosen in typical simulations.

As another distinct classification, swarm robotic models can be classified into two major groups: 1) microscopic models and 2) macroscopic models. *Microscopic models* focus on individual robots and state transitions of each robot controller are updated based on the stochastically approximated robot-robot and robot-environment interactions. The probabilities of state transitions are calculated from simple geometric configurations and with few trial experiments. Here, no group-level sensing or actuation is taken into account. On the other hand, *macroscopic models* captures the snapshot-by-snapshot pictures of whole swarm. Each snapshot presents the total number of robots in a given state. Fig. 3.15(b) shows the probabilistic macroscopic model where S_x denotes a particular state x and N_s denotes the number of robots under state S_x . Here τ represents the corresponding probability density function derived from a set of Master-Equations (Agassounon et al. 2004).

Despite a lot of attractive benefits of swarm robotic system modelling approaches, formal models of swarms, particularly probabilistic models, may not be attractive or useful for many reasons. Firstly, constructing a functional model takes time due to the need for accurate calibration of necessary parameters (which also involves running several real-experiments or simulations). Secondly, most of probabilistic models rely upon some simplifying assumptions, e.g. coverage of the area should be spatially uniform or the system should follow Markov properties i.e. the robot's future state depends only on its current state and how much time it has spent in that state. These cannot be satisfied in many practical applications e.g.

open space exploration or robots with memory. As task complexity increases the parameters space becomes large and searching for good combinations of parameters by some means, e.g. genetic algorithms, becomes more complex.

Similar to the traditional multi-robot systems, swarm robotic systems face great challenges in enabling localization, communication and interaction in group-level. For example, without the presence of any centralized localization module, such as global positioning system or indoor navigation system, it is not easy to localize precisely the position of a robot with respect to other robots or environment. Recently researchers investigated these issues and reported some novel solutions. For example, Spears et al. (2006) reported a novel technique based on trilateration for localization of swarm robots using ultrasonic and radio-frequency transceivers. Schmickl et al. (2006) reported hop-count and bio-inspired strategies for collective perception or how a swarm robot can join multiple instances of individual perception to get a global picture. Because of the similarity of the problems in both traditional multi-robot system and swarm robotic system, the issues of task-allocation and communication of both types of multi-robot system have been presented in Sec. 3.2 and Sec. 3.3 respectively.

In this dissertation, the swarm robotic system approach has been followed for designing robot group behaviours and solving related issues. The behaviour-based approach has been chosen for designing robot controllers (Chapter 4) that rely on GPS-like overhead camera-based solution to fulfil their localization needs. In this dissertation, a real robotic system has been modelled considering their spatial, embodied and microscopic properties. No macroscopic simulation or analysis of the robot group has been conducted. The autonomous robot group employed in this thesis meets all the criteria of a swarm robotic system mentioned by (Sahin and Spears 2005) except the communication issue. The task-allocation model used in this thesis does not depend on local communication strictly. The proposed MRTA solution and multi-robot communication and sensing strategies have been presented in Chapter 5 and Chapter 6.

3.2 Multi-robot task allocation

Since 90s, MRTA is a common research challenge that tries to define the preferred mapping of robots to tasks in order to optimize some objective functions (Gerkey and Mataric 2004). Many control architectures have been solely designed to address this task-allocation issue from different perspectives. Based-on the high-level design of those solutions, here researches on MRTA have been classified into two major categories: i) predefined or intentional task-allocation and ii) bio-inspired self-organized task-allocation.

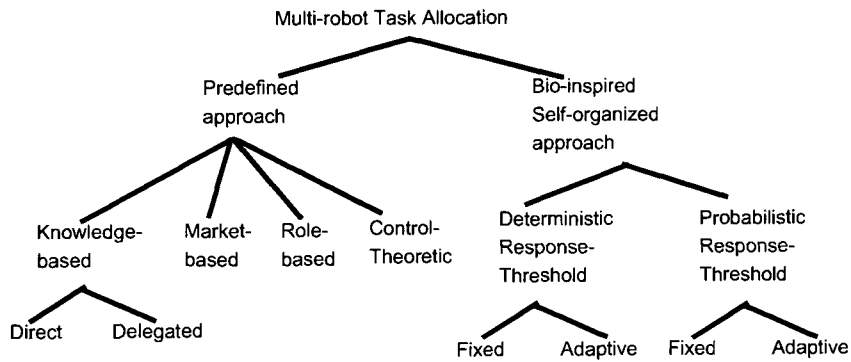


Figure 3.16: Classification of MRTA

Fig. 3.16 illustrates the proposed classification. This classification has been adopted from Shen et al. (2001), but the sub-categories used here are different since Shen et al. proposed the classification for multi-agent system alone that does not take the spatiality and embodiment of agents into account. Under each of the sub-categories of MRTA there are many inter-connected issues that need to be addressed by the system designer. In the following subsections, these two major categories and their key issues with some example MRTA solutions have been discussed.

3.2.1 Predefined task-allocation

In most of the traditional multi-robot system, task allocation is done using well-defined models of tasks and environments. Here it is assumed that the system designer has the precise knowledge about tasks, robot-capabilities etc. Many flavours

of the type of task-allocation can be found in the literature. Below a few well-acknowledged works have briefly been discussed.

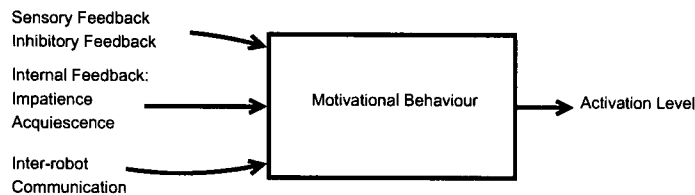


Figure 3.17: Motivational behaviour in ALLIANCE. From Parker (1998).

Knowledge-based and multi-agent based approaches

In this approach knowledge-based techniques are used to represent tasks, robot capabilities etc. One of the early well-known MRTA architecture of this category was ALLIANCE in which each robot models the ability of team-members to perform tasks by observing their current task performances and collecting relevant task quality statistics e.g. time to complete tasks (Parker 1998). Robots use these models to select a task that benefit the group as a whole. As shown in Fig. 3.10, ALLIANCE architecture, implemented in each robot, delineates several mathematically modelled behaviour sets, each of which corresponds to some high-level task-achieving function.

In ALLIANCE, the concept of motivational behaviour was introduced as a mechanism to choose among these high level behaviours. As shown in Fig. 3.17, each motivational behaviour had a number of inputs and one output. The output, i.e. the activation level corresponding behavioural set, was activated once a predefined threshold was passed. At the same time, all other behavioural sets became inhibited for allowing that selected behavioural set to complete its task. The input of the behavioural sets was ranged from sensory reading to robot-robot broadcast communication of state-information.

Internal behaviours e.g. *impatience* and *acquiescence* were also used to evaluate the motivation of a robot to select a high-level behaviour set. Impatience encouraged individual robots to perform a task that was not selected by any other robot of the team and a robot's acquiescence of a task was increased when a robot selected to perform it. Moreover, robots had the ability to override the inhibitory

signal from another robot if a task assigned to other robot was not being completed to a desired level (e.g. when a robot stalled). In case of unsatisfactory self-progress, i.e. not doing any significant progress in a task, robots were able to switch from that task to a different one.

This system was deployed to a mock hazardous waste clean up and achieved fault-tolerant distributed task performance of the robot team. L-ALLIANCE, an extension of this system was also developed to enable robots to learn from the observations of a set of task-performance metrics (Parker 1995).

Similar to ALLIANCE, multi-agent based task allocation also use both centralized and decentralized approaches for allocating tasks among its peers. Shen et al. (2001) presented a detailed categorization where in a multi-agent system task allocation can be done by using various agents ranging from a central supervising agent or a few mediator agents to all independent agents.

In case of centralized systems, the central supervisor (or a group of mediators) must have the necessary system knowledge, e.g. the capabilities and availabilities of all agents and the descriptions of tasks. This scheme gives a well coordinated, consistent and optimized task-allocation but reduces the reliability, fault-tolerance and scalability of the system. On the other hand, in case of distributed task-allocation, each agent can assign a task *directly* to another agent provided that all of them have precise knowledge about others. This approach is very expensive for large number of agents since it requires all agents to have huge processing power and communication bandwidth which is not practical.

Alternatively, agents can know only a few agents and *delegate* a task to these known peers so that a suitable agent can be found who has sufficient capabilities and free resources to do this task. This task-allocation by delegation also suffers from poor performance due to the use of time-consuming search algorithms. This approach also assumes the availability of high communication bandwidth which is not available in large systems.

Market-based approaches

As a feasible alternative to the above common multi-agent based task-allocation techniques, many researchers have been following the market-based bidding approach Dias et al. (2006). Originated from the Contract-Net Protocol, market-

based approach can be implemented as a centralized auctioning system or as a combination of *a few auctioneers – all bidders* or, independently *all auctioneers – all bidders*. For example, in a completely distributed system, when a robot needs to perform a task for which it does not have necessary expertise or resources, it broadcasts a task-announcement message, often with an expiry time of that message. Robots, that received the message and can perform that task, return a bid message. The initiating robot or *manager* selects one (or more) bidder, called as *contractor*, and offers the opportunity to complete the task. The choice of contractor is done by the manager with a mutual agreement with contractor that maximizes the individual profits.

In market-based approach, high-level communication protocol is necessary to define several types of messages with structured content. In centralized market-based approach there is only one manager that can be an external supervising agent or one of the robots. While market-based approach consume more resources it usually produces more efficient task-allocations. Anonymous robots can be selected for tasks and these can be different in each bidding cycle.

Role or value-based task-allocation

In this type of task-allocation each role assumes several specific tasks and each robot selects roles that best suit their individual skills and capabilities (Chaimowicz et al. 2002). In this case, robots are typically heterogeneous, each one having variety of different sensing, computation and effector capabilities. Here robot-robot or robot-environment interactions are designed as a part of the organization. In multi-robot soccer (Stone and Veloso 1999), positions played by different robots are often defined as roles, e.g. goal-keeper, left/right defender, left/right forwarder etc. The robot, best suited and in closest proximity to available roles/positions, selects to perform that role.

Control-theoretic approaches:

In this type of task-allocation systems, a model of the system is usually developed that converts the task specification into an objective function to be optimized. This model typically uses the rigid body dynamics of the robots assuming the masses and other parameters well-known. Control laws of individual robots are derived

either by analytically or by run-time iterations. Unlike most other approaches where task-allocation problem is taken as discrete, control-theoretic approaches can produce continuous solutions. The formalisms of these systems allow system designer to check the system's controllability, stability and related other properties. These systems typically use some degree of centralization, e.g. choosing a leader robot. Example of control-theoretic approach include: multi-robot formation control (Belta and Kumar 2004), multi-robot box-pushing (Pereira et al. 2003) etc.

Predefined task-allocation through few other approaches are also present in the literature. For example, inspired by the vacancy chain phenomena in nature, Dahl et al. (2004) proposed a vacancy chain scheduling algorithm for a restricted class of MRTA problems in spatially classifiable domains.

3.2.2 Bio-inspired self-organized task-allocation

Task performance in self-organized approaches relies on the collective behaviours resulted from the local interactions of many simple and mostly homogeneous (or interchangeable) agents. Robots choose their tasks independently using the principles of self-organization, e.g. positive and negative feedback mechanisms, randomness (recall Sec. 2.1.1). Moreover interaction among individuals and their environment are modulated by the stigmergic, local and broadcast communications (more in Sec. 3.3). Among many variants of self-organized task-allocation, most common type is response threshold-based task-allocation (Bonabeau et al. 1999).

In this approach, a robot's decision to select a particular task depends largely on its perception of stimulus (demand for a task) and its corresponding response threshold for that task. Below, the most common forms of threshold-based task-allocation: deterministic response-threshold and probabilistic response-threshold techniques has been described. Both of them can use the fixed values of response-thresholds or they can adapt their response-thresholds over time based on a suitable learning or adaptation mechanisms.

$$\sigma(r, e) = \frac{1}{d(r, e)} \quad (3.1)$$

$$\theta_e = \frac{1}{|D_r|} \quad (3.2)$$

Deterministic response-threshold approach

In this approach, each robot has a fixed or deterministic activation threshold for each task that needs to be performed. It continuously perceives or monitors the stimulus of all tasks that reflect the relative urgencies of tasks. When a particular task-stimuli exceeds a predefined threshold the robot starts working on that task and gradually decreases this stimuli. When the task-stimuli falls below the fixed threshold the robot abandons that task. This type of approach has been effectively applied in foraging (Krieger and Billeter 2000, Liu et al. 2007), aggregation (Agassounon and Martinoli 2002). This fixed response-threshold can initially be same for all robots (Jones and Mataric 2003), or they can be different according to robot capabilities or configuration of the system (Krieger and Billeter 2000).

In event-handling domain Kalra and Martinoli (2007) show how task-stimulus can be encoded in mathematical equations. Eq. 3.1 encodes the stimuli of robot r for task-urgency perception event e , $(\sigma(r, e))$ as inversely proportional to the distance between the robot and the event occurring place. Eq. 3.2 gives the threshold value θ_e (based on a predefined distance value D_r) under which robots select this particular task or event.

Unlike maintaining a fixed response-threshold, adaptive response threshold model changes or adapts the threshold over time. Response-threshold decreases often due to performance of a task and this enables a robot to select that particular task more frequently or in other words it learns about that task (Bonabeau et al. 1999, Agassounon and Martinoli 2002).

Probabilistic Response-Threshold

Unlike deterministic approach, where robots always respond to a task-stimuli that has a largest stimulus above the threshold, probabilistic approach offers a selection process based-on a probability distribution. For example, in probabilistic response, robots can respond to an event e with probability p_e , as outlined in Eq. 3.3.

$$p_e = \frac{\sigma(r, e)^n}{\sigma(r, e)^n + \theta_e^n} \quad (3.3)$$

Here θ_e is the threshold and n is the non-linearity of the response. Thus, robots always have small nonzero probabilities for all tasks.

In this dissertation this approach has been followed with an on-line adaptation mechanism which has been outlined in Chapter 5.

3.2.3 Comparisons of MRTA solutions

From the vast amount of literature on MRTA, the level of complexities of MRTA issue can be assumed. In fact researchers generally agree that the MRTA is a *NP-hard* problem where optimal solutions cannot be found quickly for large problems (Gerkey and Mataric 2004, Parker 2008). But why have so many variants of MRTA solutions been evolved?

In order to answer this question, first one needs to look into the contexts from where these MRTA solutions are originated. Most predefined task-allocation solutions are proposed within the context of a known or controlled environment where the modelling of tasks, robots, environments etc. becomes feasible. Note that here tasks can be arbitrarily complex that often require relatively higher sensory and processing abilities of robots. Robot-team can consist of homogeneous or heterogeneous individuals, having different capabilities based on the variations in their hardware, software etc. But the uncertainty of the environment is assumed to be minimum.

On the other hand, bio-inspired self-organized MRTA solutions are free from extensive modelling of environment, tasks or robot capabilities. Most of the existing research considers very simple form of one global task e.g. foraging, area cleaning, box-pushing etc. This is due to the fact that major focus of this approach is limited mainly to design individual robot controllers in such a way that a few simple or *specific* tasks can be accomplished. More research is needed to verify the capabilities of self-organized approach in doing multiple complex tasks. At this moment, the bottom line remains as “select simple robots for simple tasks (self-organized approach) and complex robots for complex tasks (predefined approach)”.

Both of the above task-allocation approaches expose their relative strengths and weaknesses when they are put under real-time experiments with variable number of robots and dynamic tasks. In an arbitrary event handling domain, Kalra and Martinoli (2007) compared between self-organized and predefined market-based task-allocation, where they found that predefined task-allocation was more efficient

when the information was accurate, but threshold-based approach offered similar quality of allocation at a fraction of cost under noisy environment.

Gerkey and Mataric (2003) presented a comparative study of the complexity and optimality of key architectures, e.g. ALLIANCE (Parker 1998), BLE (Werger and Mataric 2001), M+ (Botelho et al. 1999), MURDOCH (Gerkey and Mataric 2002), First piece auctions (Zlot et al. 2002) and Dynamic role assignment (Chaimowicz et al. 2002), all of them relied upon predefined task-allocation methods. The computational and communication requirements of these MRTA solutions were expressed in terms of number of robots and tasks. Although this study does not explicitly measure the scalability of those key architectures, it clearly shows that many predefined task-allocation solutions will fail to scale well in challenging environments when the number of robots and tasks will increase, under the given limited overall communication bandwidth and processing power of individual robots.

From above discussions one can see that, self-organized task-allocation methods are advantageous as they can provide fully distributed, scalable and robust MRTA solutions through redundancy and parallelism in task-executions. Moreover, the interaction and communication requirements of robots can also be kept under a minimum limit. Thus one can say that for large multi-robot system, self-organized task-allocation methods can potentially be selected, if a system designer can divide his complex tasks into simple pieces that can be carried out by multiple simple robots in parallel with limited communication and interaction requirements.

3.2.4 A three-axes taxonomy of MRTA solutions

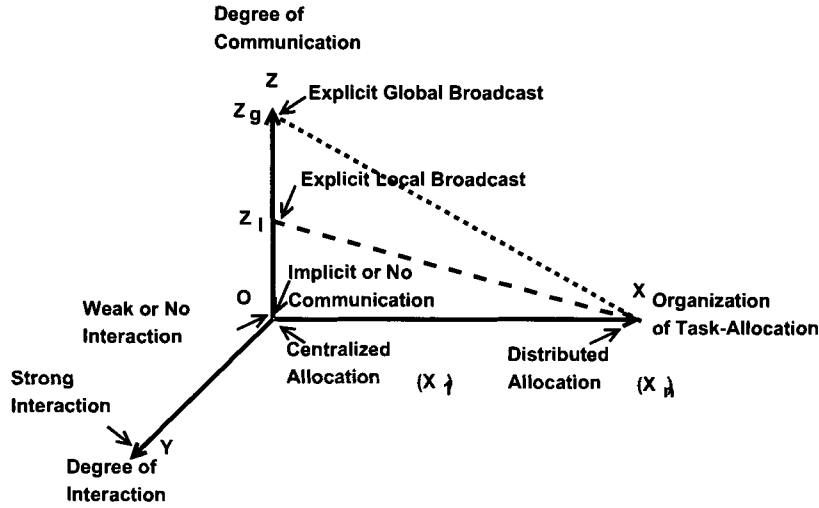


Figure 3.18: Three major axes of complexities in MRTA

In order to characterize both predefined and self-organized approaches in terms of their deployment, three distinct axes have been proposed: i) organization of task-allocation (X), ii) degree of interaction (Y) and iii) degree of communication (Z). Fig. 3.18 depicts these axes with a reference point O . These axes can be used to measure the complexities involved in various kinds of MRTA problems and the design of their solutions.

In Fig. 3.18, X axis represents the number of active nodes that provides the task-allocation to the group. For example, in any predefined task-allocation approach, one can use one external centralized entity or one of the robots (aka leader) to manage the task-allocation. In many predefined methods, e.g. in market-based systems, multiple nodes can act as mediators or task-allocators that have been discussed before. Under predefined task-allocation approach, a small number of robots can have fully distributed task-allocation where each robot acts as an independent task-allocator (e.g. as discussed before in ALLIANCE architecture).

Most of the self-organized task-allocation methods are fully distributed, i.e. they allocate their tasks independently without the help of a centralized entity. However, they might be dependent on external entities for getting status or descriptions of tasks. Recent studies on swarm-robotic flocking by Çelikkanat et al.

(2008) show that a swarm can be guided to a target by a few informed individuals (or leaders) while maintaining the self-organizing principles of task-allocation. Task-allocation of a swarm of robots just by one central entity may be rare since one of the major spirits of swarm robotic system is to become fully distributed.

In Fig. 3.18, Y axis corresponds to the level of robot-robot interaction present in the system. As it is mentioned before in Sec. 3.1.2, interaction can be classified into various levels: collective, cooperative, coordinative and collaborative. The presence of interaction can be due to the nature of the problem, e.g. cooperation is necessary in co-operative transport tasks. Alternately, this interaction can be a design choice where interaction can improve the performance of the team, e.g. cooperation in cleaning a work-site is not necessary but it can help to improve the efficiency of this task.

Y axis can also be used to refer to the degree of coupling present in the system. In case of collective interaction, robots merely co-exist, i.e. they may not be aware of each other except treating others as obstacles. Many other multi-robot systems are loosely-coupled where robots can indirectly infer some states of the environment from their team-mates' actions. But in many cases, e.g. in co-operative transport, robots not only recognize others as their team-mates, but also they coordinate their actions. Thus they form a tightly coupled system. This level of interaction and coupling also gives the information about potential side-effects of failure of an individual robot. Tightly coupled systems with high degrees of interactions among the robots suffer from the performance loss if some of the robots are removed from the system.

The Z axis of Fig. 3.18 represents the communication overhead of the system. This can be the result of the interactions of robots under a given task-allocation method. It is discussed before that various task-allocation methods rely upon variable degrees of robot-robot communications. On the other hand, the communication capabilities of individual robots can limit (or expand) the level of interaction that can be made in a given group. Thus in one way, considering the interaction requirements of a MRTA problem, the system designer can select suitable communication strategies that both minimizes the communication overhead and maximizes the performance of the group. And in another way, the communication capabilities of robots can guide a system designer to design interaction rules of robot teams,

e.g. the specification of robot's on-board camera can determine the degree of possible visual interactions among robots. The suitable trade-offs between these two axes: communication and interaction can give a balanced design of any MRTA solutions.

The central issue of this thesis is to determine the role of communication and sensing strategies under an adaptive response-threshold task-allocation method. So here the benefits of traversing along the various axes of Fig. 3.18 have been examined. In this dissertation, two distinct lines have been explored: i) distributed task-allocation, with no direct robot-robot interaction and communication, say line OX_n (n being the number of robots) and 2) distributed task-allocation, with no direct robot-robot interaction, but varying degrees of local communications, say line X_nZ_l (Z_l being a local broadcast communication strategy that involves l number of peers in communication). The MRTA experiments along OX_n and X_nZ_l can be found in Chapter 5 and Chapter 6. The issue of communication in a multi-robot system is presented in more detail in next section.

3.3 Communication in multi-robot system

Communication plays an important role for any high-level interaction (e.g. co-operative or coordinative) among a multi-robot team (Arkin 1998). This is not a prerequisite for the group to be functioning, but often act as a useful component of multi-robot system. The characteristics of communication in multi-robot system can be presented in terms of these issues:

- Rationale of communication: *why do the robots communicate?*
- Message content: *what do they communicate?*
- Communication modalities: *How do they communicate?*
- Target recipients: *With whom do they communicate?*

Below the above issues have been discussed with a focus on how communication can lead to produce effective MRTA solutions.

3.3.1 Rationale of communication

From three kinds of communication experiments: indirect stigmergic communication, direct robot-robot state communication, and goal communication, Balch (2005) found that in some tasks communication provided performance improvements while others did not. Most of the robotic researchers generally agree that communication in multi-robot system usually provides several major benefits listed below.

1. **Improved perception:** Robots can exchange potential information (as discussed below) based on their spatial position and knowledge of past events. This, in turn, leads to improve perception over a distributed region without directly sensing it.
2. **Synchronization of actions:** In order to perform (or stop performing) certain tasks simultaneously or in a particular order, robots need to communicate, or signal, to each other.
3. **Enabling interactions and negotiations:** Communication can help a lot to influence each-other in a team that, in turn, enables robots to interact and negotiate their actions effectively.

3.3.2 Information content

Although communication provides several benefits for team-work it is costly to provide communication support in terms of hardware, firmware as well as run-time energy spent in communication. So robotic researchers carefully minimize the necessary information content in communications by using suitable communication protocols and high-level abstractions. For example in foraging, grazing and consuming experiments Balch and Arkin (1994) introduced state and goal communications. In state communication, a single bit is transmitted indicating the current state of robot (e.g. 0 transmitted when robot was in *Wander* state and 1 transmitted when robot was in *Acquire* or *Retrieve* states). In case of goal communication, the location of task was also transmitted. Here is a brief summary of potential information contents used in communication among robots.

- **Individual state:** ID number, battery level, task-performance statistics, e.g. number of tasks done.
- **Goal:** Location of target task or all tasks discovered.
- **Task-related state:** The amount of task completed, number of other robots present there etc.
- **Environmental state:** Free and blocked paths, level of interference found, any urgent event or dangerous changes found in the environment.
- **Intentions:** Detail plan for doing a task, sequences of selected actions etc.

Since a multi-robot system can be comprised of robots of various computation and communication capabilities, these information contents can vary greatly based on their individual communication modules and channel capacities.

3.3.3 Communication modalities

Robotic researchers typically use robot's on-board wireless radio, infra-red (IR), vision and sound hardware modules for robot-robot and robot-host communication. The reduction in price of wireless radio hardware chips e.g. wifi (ad-hoc WLAN 802.11 network) or Bluetooth² makes it possible to use wireless radio communication widely. In-expensive IR communication module is also typically built into almost all mobile robots due to its low-cost and suitability for ambient light and obstacle detection. IR can also be used for low bandwidth communication in short-range, e.g. keen-recognition. Most robots can also produce basic sound waves and detect it with their built-in speakers and suitable configuration of on-board microphones. Although speech-recognition is not commonly found in mobile robots yet, detection of pre-recorded sound waves can be feasible.

²www.bluetooth.com



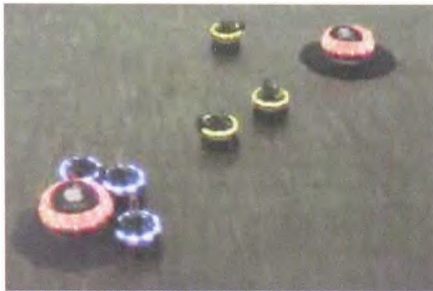


Figure 3.19: A team of s-bots communicating by light signals. From <http://lis.epfl.ch>, last seen on 01/06/2010.



Figure 3.20: A fleet of robots relying on camera (vision) for search operation. From <http://www.cs.utk.edu>, last seen on 01/06/2010.

Most of the mobile robots come with a series of LEDs, and tiny camera that can emit light signals and detect it with camera. Fig. 3.19 shows the robot-robot communication through the red and green coloured LEDs. Many robots can also detect blobs of colours and can recognize peers of other objects through the use of color-coded markers. Fig. 3.20 shows a team of robots with colour-coded markers attached on it that can be detected by the on-board camera of other robots.



(a) E-puck robots with table-lamps



(b) Sniffing Khepera III

Figure 3.21: (a) A fleet of mobile “lighting” robots moving on a large table, such that the swarm of robots form a distributed table light and (b) Distributed odour source localization by Khepera robot equipped with volatile organic compound sensor and an anemometer (wind sensor). From <http://disal.epfl.ch>, last seen 01/06/2010.

Some other researchers also tried to establish communication among robots solely relying on vision (Kuniyoshi et al. 1994). In terms of chemical communication, Lochmatter et al. (2007) showed limited success in odour-source localization, a form of detecting chemical signals (Fig. 3.21).

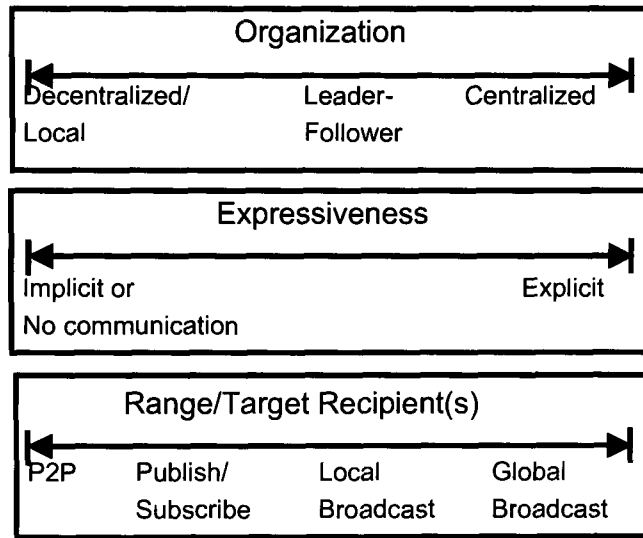


Figure 3.22: Three aspects of communication in multi-robot system

3.3.4 Communication strategies

Whatever be the communication modalities of a multi-robot system, suitable strategies are required to disseminate information in a timely manner to a target audience that maximizes the effective task-completion and minimizes delays and conflicts. A review of various communication strategies in social system has been presented in Sec. 2.1.2. Here, in order to discuss the complexities of communication strategies three independent scales, organization, expressiveness and range of communication, have been chosen. With these independent aspects, the level of complexities in communication can be measured and multi-robot systems can be classified according to its communication characteristics. Fig. 3.22 outlines these scales and they are described below.

Centralized and decentralized communications

Similar to the organization of task-allocation discussed in Sec. 3.2.4, communication in a multi-robot system can be organized using an external/internal central entity (e.g. a server PC, or a leader robot) or, a few leader robots, or by using decentralized or local schemes where every robot has the option to communicate with every other robot of the team. From a recent study of multi-robot flocking

Çelikkanat et al. (2008) have shown that a mobile robot flock can be steered toward a desired direction through externally guiding some of its members, i.e. the flock relies on multiple leaders or information repositories. Note that here task-allocation is fully decentralized i.e. each robot selects its task, but the communication structure is hybrid; robots communicate with each other and with a centralized entity.

Explicit and implicit communications

Communication in a multi-robot system can also be characterized by its expressiveness or the degree of explicitness. In one extreme it can be fully implicit, e.g. stigmergic, or on the other end, it can be fully explicit where communication is done by a rich vocabulary of symbols and meanings. Researchers generally tend to stay in either end based on the robotic architecture and task-allocation mechanism used. However, both of these approaches can be tied together under any specific application. They are highlighted below.

1. **Explicit or direct communication:** This is also known as intentional communication. This is done purposefully by usually using suitable modality e.g. wireless radio, sound, LEDs. Because explicit communication is costly in terms of both hardware and software, robotic researchers always put extra attention to design such a system by analysing strict requirements such as communication necessity, range, content, reliability of communication channel (loss of message) etc.
2. **Implicit or indirect communication:** This is also known as indirect stigmergic communication. This is a powerful way of communication where individuals leave information in the environment. This method was adopted from the social insect behaviour, such as stigmergy of ants (leaving of small amount of pheromone or chemicals behind while moving in a trail).

Local and Broadcast communications

The target recipient selection or determining the communication range or sometimes called radius of communication is an interesting issue in multi-robot system research. Researchers generally try to maximize the information gain by us-

ing larger range. However, transmission power and communication interference among robots play a major role to limit this range. The following major instances of this strategy can be used.

- **Global broadcast communication:** where all robots in the team can receive the message.
- **Local broadcast communication:** where a few robots in local neighbourhood can receive the message.
- **Publish-subscribe communication:** where only the previously subscribed robots can receive the message.
- **P2P communication:** where only the closest peer robot can receive the message.

3.3.5 Key issues in multi-robot communication

Several important issues related to communication among a multi-robot team have been identified since last decade. Some of the major issues are discussed here.

Determination of local neighbourhood

Most researchers in the area of swarm-robotic system, who use algorithms based on local-neighbourhood of communication, face this problem of defining the range of local neighbourhood. Agah and Bekey (1995) presented that larger communication range is not always optimum for some types of tasks e.g. exploration where a large number of recipient robots decreased the performance of exploration task. Yoshida and Arai (2000) provided a design of optimal communication range of homogeneous robots based on their spatial and temporal analyses of information diffusion within the context of cooperative tasks in a manufacturing shop-floor. Spatial design tried to minimize the time for information transmission and temporal design tried to minimize the information announcing time to avoid excessive information diffusion. Below Eq. 3.4 describes their optimal range $\chi_{optimal}$ as a function of information acquisition capacity of robots (c) and the probability of information output of a robot (p).

$$\chi_{optimal} = \frac{\sqrt[c]{c!}}{p} \quad (3.4)$$

Here c is an integer representing the upper-limit of the number of robots that can be the target recipients at any time without the loss of information and $\chi_{optimal}$ gives the average number of robots within the output range.

Kin recognition

Kin recognition refers to the ability of a robot to recognize immediate family members by implicit or explicit communication or sensing (Mataric 2007). In case of multi-robot system, this can be as simple as identifying other robots from objects and environment or as finding team-mates in a multi-robot soccer. This is a useful ability that helps interaction, such as cooperation among team members avoiding opponents.

Representation of languages

In case of effective communication several researchers also focused on representation of languages and grounding of these languages in physical world. Implicit communication generally has no or very little necessity of symbol grounding. In foraging experiments Liu et al. (2007) used certain cues or events to adapt the response-thresholds of robots. For example, successfully retrieving food makes a robot keep foraging and colliding with other robots makes a robot more likely to rest. These simple cues are based on dynamic events but they can hardly be adopted in complex tasks and environments. Explicit communication often uses custom hand-crafted messages by a set of symbols. Based on a shared vocabulary, they can provide the necessary meaning for the robots. For new kinds of messages one always needs to modify the symbols and shared vocabulary. In such cases knowledge representation techniques and tools can be useful to some extent (Parker 2008).

Fault-tolerance and reliability

Since every communication channel is not free from noise and corruption of messages significant attention has also been given to manage these no communication situations, such as by setting up and maintaining communication network, managing reliability and adaptation rules when there is no communication link available. In terms of guaranteeing communication, researchers also tried to find ways for a

deadlock free communication methods, such as signboard communication method (Wang 1989).

3.3.6 Role of communication in MRTA

Although researchers in the field of multi-robot system have been adopting various communication strategies for achieving MRTA solutions in different task domains, very few studies correlate the role of communication with the effectiveness of MRTA. This is due to the fact that researchers usually adopt a certain task-allocation method and they limit their use of communication strategy to either explicit global/local broadcast (in most predefined task-allocation researches) or implicit/no communication (in most self-organized task-allocation researches). In the former one, communication becomes the part and parcel of the robot-robot interactions that enable them to exchange variety of information as discussed before. But in the latter one, the environment serves as a shared memory for all robots to access information or sense the current state of the environment, mostly locally. Here MRTA solutions have been scrutinized to find out their variations in adopting communication strategies.

As mentioned in Sec. 3.2.2, Kalra and Martinoli (2007) empirically studied the comparative performance of MRTA under both predefined and self-organized approaches with event-driven simulations. They found that the accuracy of information is crucial for predefined market-based approach where every robot communicated with every other robot (i.e. global broadcast). In case of unreliable link or absence of communication, threshold-based approach performed same as market-based approach, but with less computational overhead. This indicates the dependence of predefined approach on reliable communication links. However their global broadcast strategy is not feasible for large teams of real-robots. In case of varying robot's communication range, they found that market-based approach performed well for a short communication-range where robots were able to communicate with less than a third of the total number of team-mates. Since the events are handled based on their spatial locations only, it is not clear how this strategy will perform in other task-domains.

In order to pursue MRTA, robots can receive information from a centralised source (Krieger and Billeter 2000) or from their local peers (Agassounon and

Martinoli 2002). This centralized communication system is easy to implement. It simplifies the overall design of a robot controller. However as it is mentioned before, this system has disadvantage of a single point of failure and it is not scalable. The increased number of robots and tasks cause inevitable increase in communication load and transmission delay. Consequently, the overall system performance degrades. On the other hand, uncontrolled reception of information from decentralized or local sources is also not free from drawbacks. If a robot exchanges signals with all other robots, it might get the global view of the system quickly and can select an optimal or near optimal task. This can produce a great improvement in overall performance of some types of tasks e.g., in area coverage (Rutishauser et al. 2009). But this is also not practical and scalable for a typically large multi-robot system due to the limited communication and computational capabilities of robots and limited available communication bandwidth of this type of system.

A potential alternate solution to this problem can be obtained by decreasing the number of message recipients on the basis of a local communication range. This means that robots are allowed to communicate only with those peers who are physically located within a pre-set distance. When this strategy is used for sharing task information among peers, MRTA can be more robust to the dynamic changes in the environment and energy- efficient (Agassounon and Martinoli 2002). Similar to this, Pugh and Martinoli (2009) reported a distributed multi-robot learning scenario with two cases: 1) robots were allowed to communicate with any two other robots (*Model A*) and 2) robots were allowed to communicate with all robots in a fixed radius (*Model B*). In simulation and real robotic experiments with 10 robots and communication ranges of 0.3 m, 1.0 m and 3.3 m, they showed that Model B performed better in intermediate communication range. However, this learning function in each individual robot controller was conducted in static environment. So it is not clear why intermediate communication range performs better than other ranges.

Many robotic researchers tried to use some forms of adaptation rules in local communication to avoid saturation of the communication channel, e.g. based on robot densities in a given area. As mentioned before, Yoshida and Arai (2000) tried to formalize the suitable communication range based on spatial and temporal properties of information diffusion of a given communication channel. The major focus

of this type of research is to measure the cost of communication based on some metrics, e.g. transmission time and collisions with other robots, and then regulate communication strategies or ranges dynamically ranging from global broadcast to local P2P or not doing communication at all when a huge cost is involved. These ideas are attractive to maximize information gain in dynamic environment, but there is no point of doing communication if there is little or no task-requirement. Thus maximizing information gain is not always useful or necessary for realizing effective MRTA.

Oca et al. (2005) also acknowledged the above fact within the context of their ant-based clustering experiments. They used two simple communication strategies: i) simple memory sharing by robots (shared memory access) and ii) shared use of environment maps (global sensing). In both of these cases, it was found that communication was only useful when some initial random clustering phase was passed. The accuracy of shared information in highly dynamic environment was poor and did not carry any significant advantage. In case of local memory sharing by robots, they showed that sharing information within a limited number of robots produced more efficient clusters, rather than not sharing information at all in stigmergic communication mode. However, sharing memory in a large group is not a feasible communication strategy because of the huge latencies and interferences involved in the communication channel.

3.4 Application of MRS in automation industry

Automation industry, particularly automated manufacturing domain, provides an excellent area where MRTA problem can be studied and applied. Most of the research in this area is inspired by intelligent multi-agent technology (Shen et al. 2006). A few other researchers also tried to apply the concepts of biological self-organization (Ueda 2006, Lazinica and Katalinic 2007). In this section these concepts and technologies have been highlighted, focusing mainly on physical embodiment of agents, i.e., the use of multiple mobile robots or AGVs.

3.4.1 Multi-agent based approaches

Since early 80s, researchers have been applying agent technology to manufacturing enterprise integration, manufacturing process planning, scheduling and shop floor control, material handling and so on. An agent is a software system that communicates and cooperates with other software systems to solve a complex problem that is beyond the capability of each individual agent's software system (Shen et al. 2001). Most notable capabilities of agents are autonomous, adaptive, cooperative and proactive. There exists many different extensions of agent-based technologies such as holonic manufacturing system (Bussmann et al. 2004). Here, *holon* refers to an autonomous and cooperative unit of manufacturing system for transporting, transforming, sorting and/or validating information and physical objects.

Agent based technologies have addressed many of the problems encountered by the traditional centralized manufacturing methods. They can respond to the dynamic changes and disturbances through local decision making. The autonomy of individual resource agents and loosely coupled network architecture provide better fault-tolerance. The inter agent distributed communication and negotiation also eliminate the problem of having a single point of failure of a centralized system. These facilitate a manufacturing enterprise to reduce their response time to market demands in globally competitive market.

Despite having so many advantages, agent-based systems are still not widely implemented in the manufacturing industry comparing to the other similar technologies, such as distributed objects and web-based technologies due to the lack of integration of these systems with other existing systems particularly real-time data collection system, e.g., radio frequency identification system. Another barrier is the increased cost of investment in exchange of some additional flexibility and throughput (Schild and Bussmann 2007).

A case study: Kiva material handling system

Figure 3.23: A multi-robot material handling system from Kiva systems Inc. From <http://www.kivasystems.com/>, last seen on 06/06/2010.

As a notable exception in multi-robot automation application, the Kiva material handling system³ has revolutionized the traditional warehouse order-processing jobs by replacing the old-style relatively expensive AGVs with cheaper mobile robots (Wurman et al. 2008). As shown in Fig. 3.23 hundreds of mobile robots are working in a warehouse where thousands of customer-orders are handled in real-time. The major advantages of this system over traditional material handling systems are as follows.

- Multiple orders are handled in parallel with random access to all items. This greatly simplifies the ware-house operations.
- Each worker does his job independently. No inter-dependency among workers exists which is very common in a sequential order processing system.
- Instead of having 5-10 expensive AGVs, now a company can have 30-50 mobile robots that greatly increases the productivity of the warehouse and reduces operational cost significantly.
- Real-time order processing removes any need for batch processing.
- All major benefits of a distributed system including: no single point of failure, spatial flexibility and better expandability.

³<http://www.kivasystems.com/>

Kiva material handling system has been implemented using Java-based multi-agent and AI techniques. It uses a centralized resource and task-allocation unit which assigns jobs to a mobile robot's drive-unit agent and resources to a worker's inventory-station agent using utility-based heuristics, similar to the predefined task allocation approach. Here utility is measured in terms of the cost to the warehouse owner. Spatial location of robots and inventory stations, specific task skills of certain stations, commonalities among orders etc. are taken into account to find the lowest utility cost and to make allocation decisions on-the-fly.

The control architecture of robotic drive units follows typical three layer hybrid control strategy (Simmons et al. 2002). In order to locate resources and collectively⁴ process customer orders, robotic agents communicate with each other via XML messages. About 100 types of messages have been designed to meet this communication need.

At the time of writing this dissertation, the base price of this system with 30-50 robotic drive units has been estimated as \$1M US dollars and this system has been installed about 10-20 warehouses with more than a thousand robotic units being operational⁵. Interested readers may find more on Kiva material handling system and its technical implementation in Wurman et al. (2008).

3.4.2 Biology-inspired approaches

The insightful findings from biological studies on insects and organisms have directly inspired many researchers to solve problems of manufacturing industries in a biological way. These can be categorized into two groups: one that allocates task with explicit potential fields and another that allocate tasks without specifying any potential field. Below both types of biology-inspired manufacturing system (BMS) have been discussed.

Explicit potential field based BMS

The biological evidences of the existence of potential field between a task and an individual worker such as, a flower and a bee, a food source and an ant, inspired some researchers to conceptualize the assigning of artificial potential field between

⁴Recall the collective interaction from Sec. 3.1.2 where agents are unaware of each-other, share common goals and their actions are beneficial to their team-mates.

⁵<http://www.robotictrends.com/>, last accessed on 10/06/2010.

two manufacturing resources. For example, potential field is assumed between a machine that produce a material part and a worker robot or AGV that manipulates the raw materials and finished products.

Ueda (2006) conceptualized this potential field as the attractive and repulsive forces based on machine capabilities and product requirements. Task allocation is carried out based on the local matching between machine capabilities and product requirements. Each machine generates an attractive field based on its capabilities and each robot can sense and matches this attractive field according to the requirements of a product. Potential field is a function of distance between entities. Here, self-organization of manufacturing resources occurred by the process of matching the machine capabilities and requirements of moving robots. Through computer simulations and a prototype implementation of a line-less car chassis welding, Ueda (2006) found that this system was providing higher productivity and cost-effectiveness of manufacturing process where frequent reconfiguration of factory layout was a major requirement. This approach was also extended and implemented in a supply chain network and in a simulated ant system model where individual agents were rational agents who selected tasks based on their imposed limitations on sensing.

BMS without explicit potential fields

Several other researchers did not express the above potential field for task allocation among manufacturing resources explicitly, rather they stressed task selection of robots based on the task-capability broadcasts from the machines to the worker robots. In case of Lazinica and Katalinic (2007), task capabilities are expressed as the required time to finish a task in a specific machine. They used assigned priority levels to accomplish the assembly of different kinds of products in the computer simulation of their bionic manufacturing system. In another earlier computer simulated implementation of swarm robotic material handing of a manufacturing work-cell, Doty and Van Aken (1993) pointed out several pitfalls of such a BMS system, such as dead-lock in manufacturing in inter-dependant product parts, unpredictability of task completion, energy wastage of robots wandering for tasks etc. Although most of these problems remain unsolved researchers are still exploring the concepts BMS in order to achieve a higher level of robustness, flexibility and

operational efficiency in a highly decentralized, flexible, and globally competent next generation automated manufacturing system.

In this dissertation, a manufacturing shop-floor scenario have been considered where robots are required to attend mock production and machine-maintenance jobs in different machines in an arena using their *homing* behaviours. This study significantly differs from the above works since the generic framework of self-regulation considers not only the spatial distances to tasks and their dynamic urgencies but also the learning and forgetting of agents about tasks. Moreover, unlike the above deterministic approaches, this approach uses a probabilistic method for task allocation. Detail features of this generic framework of self-regulated DOL is discussed in Chapter 5.

3.5 Summary

This chapter provides a snapshot on the broad range of researches on multi-robot systems along with the specialized reviews on communication and task-allocation in multi-robot teams. Most of the researches have been classified into two broad categories: i) traditional multi-robot system and ii) swarm robotic system. Different perspectives of these two categories have been discussed. From the critical review on the related works on MRTA, it is seen that the role of communication in producing MRTA is not well-established in the literature. A three-axis MRTA taxonomy has been proposed to address the ambiguities found in describing existing MRTA solutions. The applications of multi-robot systems in production and automation industries have briefly been reviewed here. These reviews provide a strong foundation to explain AFM in terms of existing MRTA researches and inspire to develop real-world application using the state-of-the-art multi-robot control frameworks.

Experimental Tools and Technologies

4.1 General methodological issues

4.1.1 Real robotic experiments vs. simulations

Traditionally robotic researchers use software simulation to validate their model before stepping into real-robotic experiments. Simulating a model by software code is easier and much faster compared to real-world experiments. It does not require any sophisticated hardware set-up or time-consuming software debugging. However, in recent times, the abundance of real robot hardware and other necessary tools encourages researchers to test their work in the real systems from the inception of their models. The reasons for not following the traditional “simulation first” approach have briefly been discussed below.

Firstly, contemporary state-of-the-art agent-based simulation packages are essentially discrete-event simulators that execute models serially in a computer’s CPU (Lysenko and DSouza 2008). However in real-world systems agents act in parallel and give the robots: “what you see is what you act upon” environment. In simulations that might not be case.

Secondly, the robot-robot and robot-environment interactions are complex and completely unpredictable in real environment than their simulation counterparts. Unexpected failures will not occur in simulations that can either cause positive or negative effects in the experimental results (Krieger and Billeter 2000).

Thirdly, it is not easy to faithfully model communication behaviours of agents in simulations. Short-range Bluetooth communication system used in this study is subject to dynamic noise and limited bandwidth conditions.

Fourthly, the dynamic environment conditions, e.g., increased physical interferences of larger team of robots, can also influence the experiment's outcome which may not become obvious in simulations.

Finally, the author of this thesis believes that the algorithm tested in real-robots can give strong confidence for implementing them in real-robotic systems and later on, this can also be extended or verified in simulations. However, conversely speaking, algorithm implemented in simulation has no warranty that this might work practically with large number of robots.

4.1.2 Design of multi-robot system

Task specification. In this dissertation, the target multi-robot system has been designed for emulating manufacturing shop-floor scenario where robots are required to perform some tasks in different machines while maintaining an effective MRTA. The notion of *tasks* has been kept very simple as e-puck robots are not capable of doing many high-level practical tasks e.g. gripping or recognizing objects, carrying loads etc. Many researchers use additional hardware modules with their robots e.g., gripper to collect a puck or any small objects from floors. Rather than emulating such trivial acts, more focus has been given on the generic and abstract implementation of AFM, that can later be fitted to do any real job. Doing real manufacturing tasks has been kept as a future research issue.

By “doing a task” e-puck robots usually perform two functions: 1) navigate to a fixed task-location in the experiment arena (hereafter called *navigation*), and 2) they do so by avoiding any dynamic obstacle hereafter called *obstacle avoidance*. In robotics literature this is considered as an equivalent of *homing* behaviour (e.g. Mataric (1994)). Depending on the time-out value of doing a task, a robot can wait at task-location if it arrives earlier or may switch to a different task and change direction on-the-fly. These symbolic tasks can be mapped to any suitable real task in multi-robot manufacturing domain, such as, material handling or attending a machine for various production or maintenance jobs e.g., welding different machine parts, cleaning or doing maintenance work of a machine etc.

Robot-team specification. Based on the task-requirements a simple miniature mobile robot, e-puck (Mondada et al. 2009), has been selected that can do the above navigation tasks avoiding any dynamic or static obstacle. According to the classification of Dudek et al. (1996) the proposed system can be described as below.

- **SIZE-INF:** The robot team size is larger than 2 robots and the number of potential tasks. Actually 8 to 16 robots are used in two sets of experiments and the average number of robots per task has been kept as 4.
- **COM-INF:** Robots can communicate with any other robot.
- **TOP-ADD:** Every robot can communicate with any other robot by name or address (link path). Naming of robot's communication link path is assumed to follow any simple convention, e.g., /robot1, /robot2 etc.
- **BAND-INF:** Every robot can communicate with other robot with as much bandwidth as necessary. Since robots need to exchange simple messages this bandwidth issue is ignored.
- **ARR-DYN:** Robot can change the arrangement dynamically.
- **CMP-HOM:** Each robot is initially identical in both hardware and software, but they can become different gradually by learning different tasks by different degrees (in software).

System set-up and organization. The swarm robotic principles has been chosen for controlling the group without having the necessity for local communication and interaction. The details of control architecture has been described in Sec. 4.3. Since e-puck robots cannot localize themselves by their own hardware their instant position and orientation (*pose*) data information have been provided from a multi-robot tracking system. Sec. 4.2.1 describes about the tracking system. This system also helps in recording and logging individual robot's task performance and communication patterns. Bluetooth communication link, built-in with e-puck robots, has been used for host PC to robot communication. Robot can also communicate with each-other physically over Bluetooth. However, that mode of communication is not used. Instead, inter-robot communication is done virtually in host PC's D-Bus IPC channel. This has been illustrated in Sec. 4.2.2.

4.2 Enabling software tools and frameworks

4.2.1 SwisTrack: a multi-robot tracking system

In almost all types of robotic experiments, vision-based tracking becomes the standard feasible solution for tracking robot positions, orientations and trajectories. This is due to the low cost of camera hardware and availability of plenty of standard image-processing algorithms from computer vision and robotic research community. However, setting-up a real-time multi-agent tracking platform using existing software solutions are not a trivial job. Commercial systems tend to provide sub-millimetre level high precision 3D tracking solutions with a very high price ranging from 40-50 thousands of pounds which is typically greater than the annual budget of a research project! Besides robotics researchers prefer open-source solution to closed-source proprietary one due to the need for improving certain algorithms and applications continuously.

Another line of solution can be borrowing certain open-source tracking code from XYZ lab. But it typically ends up with a lot of frustration while tuning parameters manually, fixing the lab lighting conditions, seeing bad performance of programs that frequently leak memory or show segmentation fault and so forth. Graphical user interface (GUI) or camera calibration can hardly be found in those so-called open-source applications. The third option for solving this tracking issue becomes “re-inventing the wheel” or hiring some research students to build a system from the scratch. Certainly this is also not feasible due to the limitations in time, resource and skill needed to produce such a solution. Another big issue is the expiration of research fellowship before doing any practical research!

From the beginning of this research, the above types of problems have been found. Several commercial motion capture solution providers (including, Vicon¹) offered very high price quotes. Some well-known and some not-so-well-known open-source object tracking systems were tested which including ARTag², AR-ToolKitPlus³. A custom version of Open-CV algorithms was developed for tracking colour blobs based on a GNOME application Cynbe’s vision-app⁴.

¹<http://www.vicon.com>

²<http://www.artag.net>

³http://studierstube.icg.tu-graz.ac.at/handheld_ar/artoolkitplus.php

⁴<http://muq.org/cynbe/vision-apps>

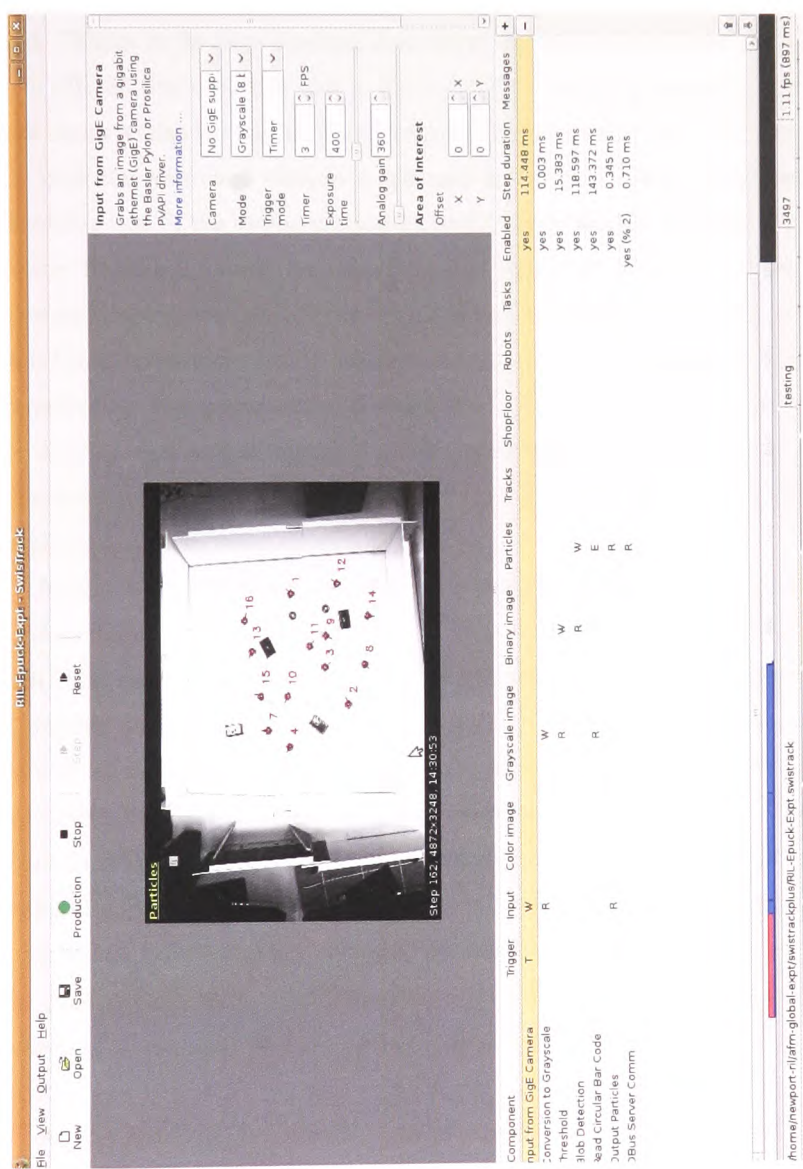


Figure 4.1: SwisTrack tracking a team of 16 robots under Ubuntu Linux 9.10 OS.

However, those algorithms failed to scale well due to the fluctuations in lighting conditions, lack of proper integration of all related components and some other issues. Finally, SwisTrack (Lochmatter et al. 2008) has been chosen. This is a state-of-the-art open-source multi-agent tracking platform developed at EPFL, Switzerland. Thanks to the hard working developers and generous sponsors of EPFL who have offered this excellent tool to the scientific research community and empowered many researchers to track multi-agents or multi-robots out-of-the-box.

With the improved version 4 released in February 2008, SwisTrack is now becoming one of the *de-facto* standard tool for multi-robot tracking. Being open-source, flexible, modular and customizable, SwisTrack provides a clean development and deployment path for tracking marked or marker-less objects in real-time. SwisTrack is written in C++ using common C/C++ programming libraries and frameworks. The component-based modular development style is very powerful for developing a custom algorithm and wrap it in a custom component. The GUI provides a rich user interface with a clean separation between algorithmic code and parameters used in those algorithms (Fig. 4.1).

In Sec. 4.2.2 it is shown that how one can append custom communication components in the image processing pipeline (Fig. 4.4). This pipeline can be compared with Unix command processing where output of one command becomes the input of another subsequent command and many commands form a chain or pipeline. Here in SwisTrack, at first an image capturing component grab camera image using USB, IEEE1394/Firewire, GigE or other supported interfaces. Then subsequent SwisTrack components work on this image and do various processing e.g., background subtractions, colour conversions, blob-detection, tracking etc. These components follow standard computer-vision algorithms and can be used without any code modification. But if necessary they can also be modified or optimized though changing source code and/or tuning parameters on-the-fly in SwisTrack GUI.

As shown in Fig. 4.1, this GUI can take parameters in real-time and update images. Final output from images, e.g., object position, orientation, trajectory etc. can be sent over standard communication interfaces, e.g. TCP/IP, NMEA etc. SwisTrack has a lot of other features, such as multi-camera tracking, remote-control of SwisTrack over TCP/IP etc. which are documented in SwisTrack Wiki-book

documentation.⁵



(a)



(b)

Figure 4.2: The experiment arena captured by (a) a GigE4900C camera mounted on 3m high ceiling (b) an ordinary camcorder.

⁵<http://en.wikibooks.org/wiki/Swistrack>

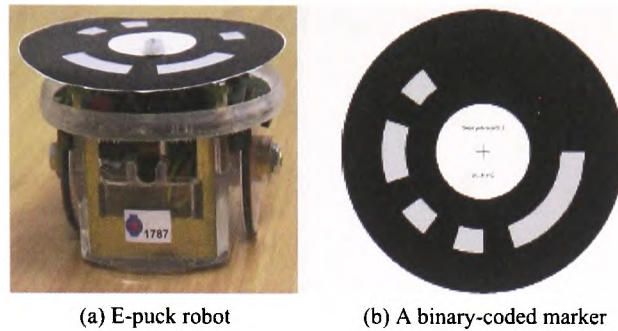


Figure 4.3: (a) The e-puck robot with SwisTrack marker on top, (b) A binary coded marker that can be tracked by an overhead camera using SwisTrack.

As shown in Fig. 4.2, SwisTrack has been setup with Prosilica GigE camera GE4900C and configured it for tracking e-puck robots with their on-top markers (Fig. 4.3). These markers are binary-coded numbers (aka *circular bar-codes*) that have certain binary bits or chip-lengths. Twenty bits chip-lengths is used. In order to uniquely identify the position and orientation of these markers, these binary numbers are encoded with a fixed hamming distance, i.e. differences in bits of any two binary numbers. A fixed hamming distance of 6 bits is selected. As shown in Fig. 4.3, these markers are 8cm diameter and clearly identified and tracked by SwisTarck from a camera image resolution of 4872x3248.

SwisTrack has no component for grabbing Prosilica GigE camera frames. So a Prosilica GigE input component is developed using Prosilica SDK and OpenCV library. The version of SwisTrack (May 2008) has worked pretty well except a few minor things, such as real-time configuration changing was very unstable due to a large camera image size (16MB/frame). In order to avoid that necessary configurations is put in SwisTrack project files that is loaded by SwisTrack in the beginning of an experiment run.

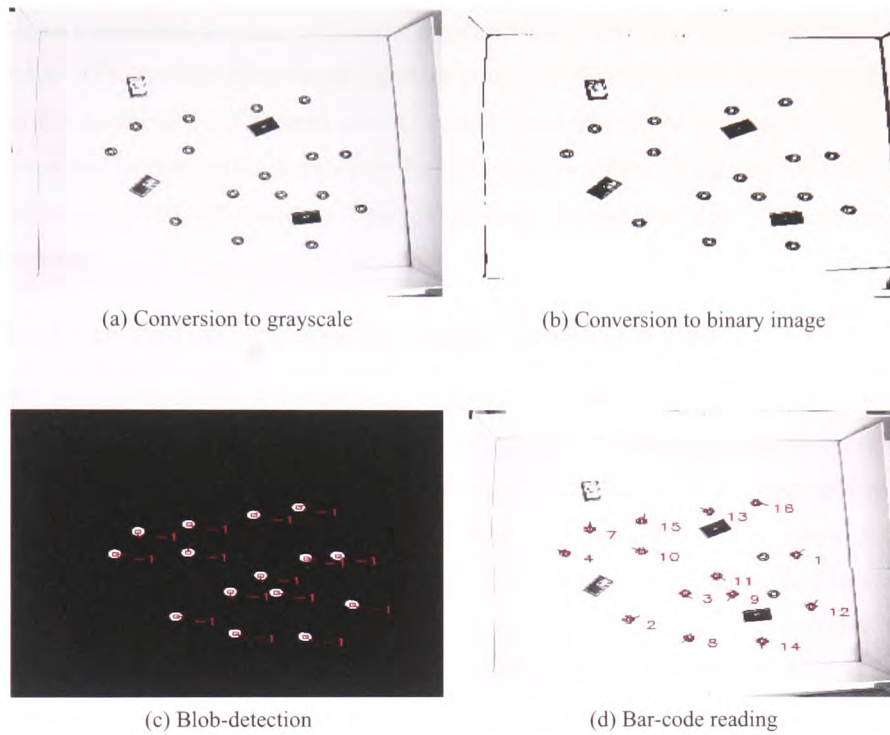


Figure 4.4: SwisTrack image processing pipeline uses (a) conversion to grayscale image, (b) threshold the grayscale image to get binary image, (c) blob detection and (d) circular bar-code reading algorithms.

Fig. 4.4 shows the components that have been used throughout AFM experiments. Along with the standard blob detection and circular bar-code reading components, custom D-Bus server communication component is used that send pose information to D-Bus inter-process communication (IPC) channels (Sec. 4.2.2). These components require a little tuning of few parameters, e.g. blob size, blob counts etc. They can be done once and saved in component configuration files for loading them in next runs.

Although SwisTrack provides a wide range of components for object trajectory tracking jobs, camera images has been saved as video from within SwisTrack due to heavy CPU load and memory usage. Besides, the video output component of the version of SwisTrack cannot produce smooth video files in this set-up. So, occasionally image frames are saved in files and in most of the experiments, Ubuntu

Linux's standard desktop tool, *recordmydesktop*⁶ is used for capturing screen as video. The standard fluorescent lightings set-up of the arena has seemed sufficient for the overhead GigE camera and the interferences of outside sun-lights have been prevented by putting black blinds in the laboratory windows. This GigE camera has been configured automatically through standard configuration files while program start-up.

4.2.2 D-Bus: an inter-process communication protocol

IPC among various desktop software components enable them to talk to each other and exchange data, messages or request of services. Technological advancements in computer and communication systems now allow robotic researchers to set-up and conduct experiments on multi-robot systems from desktop PCs. Many compelling reasons, including open licensing model, availability of open-source tools for almost free of cost, community support etc., make Linux as an ideal operating system for robotics research. However the integration of heterogeneous software components in Linux desktop becomes a challenging issue, particularly when each robot-control software needs sensory and other data input from various other software components (e.g. pose data from a pose-tracker, task information from a task-server etc).

Traditional IPC solutions in a standard Linux desktop, e.g. pipes, sockets, X atoms, shared memory, temporary files etc. (hereafter called *traditional IPCs*), are too static and rigid to meet the demand of a dynamic software system (Wittenburg 2005). On the other hand, complex and heavy IPC like CORBA⁷ fails to integrate into development tool-chains efficiently. They also require a steep learning curve due to their complex implementations.

Besides, the failure of *Desktop Communication Protocol* in system-wide integration and interoperability issues encouraged the development of the D-Bus message bus system, D-Bus for short (Pennington et al. 2010). This message bus system provides simple mechanisms for applications to talk to one another. In this thesis the simplicity and power of D-Bus have been exploited for running a large MRS.

⁶<http://recordmydesktop.sourceforge.net/>

⁷<http://www.omg.org/gettingstarted/corbafaq.htm>

Traditional IPCs lack the important requirements of IPC among several heterogeneous software components of a large MRS.

- Firstly, real-time support in IPC is critical for connecting time-critical control applications. For example, a multi-robot tracking system can share robot pose information with a robot-controller client (RCC) through shared memory (SHM). This pose information can be used to help navigating a robot in real-time. However if that multi-robot tracking system crashes and stops writing new pose information into the SHM, RCC has no default mechanism to know that SHM data is outdated. Some form of reference counting mechanism can be used to overcome this issue, but that makes the implementation of RCC complicated and error-prone.
- Secondly, IPC must be scalable so that adding more software components (thus more robots, sensors, etc.) in the information sharing game do not affect the overall system performance. But clearly this cannot be achieved through traditional IPCs, e.g. SHM or temporary files, as the access to computer memory and disk space is costly and time consuming.
- Thirdly, IPC should be flexible and compatible enough to allow existing software components to join with newly developed components in the information process sharing without much difficulties. Again existing IPCs are too static and rigid to be integrated with multiple software components. Besides, incompatibility often arises among different applications written in different programming languages with different IPC semantics.
- Fourthly, IPC should be robust, fault-tolerant and loosely coupled so that if one ceases to work others can still continue to work without strange runtime exceptions.
- Finally, IPC should be implemented simply and efficiently in any modern high level programming languages, e.g., C/C++, Java, Python. Practically, this is very important since IPC will be required in many places of code and application programmers have little time to look inside the detail implementation of any IPC.

In this dissertation, a scalable and distributed multi-robot control architecture is presented. This is built upon D-Bus IPC and works asynchronously in real-time. By using only the signalling interfaces, SwisTrack can be integrated with a multi-robot control framework. All software components are loosely coupled and unlike traditional IPCs, one does not depend on another for setting up and shutting down IPC infrastructure. For example, in case of SHM one software component explicitly needs to set-up and clean-up SHM spaces. In case of D-Bus any software component can join and leave in the information sharing process at any time. Each component implements its own fall-back strategy if desired information from another component is unavailable at any time. Based on a thin C API, D-Bus also provides many binding in common programming languages. In this work, *dbus-python*, a Python binding for D-Bus, is used that provides a very clean and efficient IPC mechanism.

D-Bus Overview

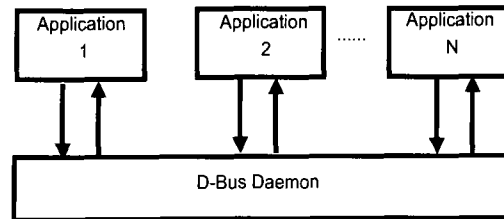


Figure 4.5: A typical view of D-Bus message bus system.

D-Bus was designed from scratch to replace CORBA and Desktop Communication Protocol to fulfil the needs of a modern Linux system. D-Bus can perform basic application IPC as well as it can facilitate sending events, or signals, through the system, allowing different components in the system to communicate. D-Bus is unique from other IPCs in several ways: e.g. 1) the basic unit of IPC in D-Bus is a message, not a byte stream, 2) D-Bus is bus-based and 3) It has separate system-wide and user/session-wide bus (Love 2005). The simplest form of D-Bus communication is process to process. However, it provides a daemon, known as the *message bus daemon*, that routes messages between processes on a specific bus. In this fashion, a bus topology is formed (Fig. 4.5). Applications can send to or

listen for various events on the bus.

D-Bus specification (Pennington et al. 2010) provides full details of D-Bus message protocols, message and data types, implementation guidelines etc. Here some relevant parts of this specification have been discussed. Fig. 4.5 an example of D-Bus system structure.

Here a few basic D-Bus terminologies have been introduced from D-Bus literature.

1. **D-Bus Connection:** *DBusConnection* is the structure that a program first uses to initiate talking to the D-Bus daemon, Programs can either use `DBUS_BUS_SYSTEM` or `DBUS_BUS_SESSION` to talk to the respective daemons.
2. **DBus Message:** It is simply a message between two process. All the D-Bus intercommunication are done using *DBusMessage*. These messages can have the following four types: method calls, method returns, signals, and errors. The *DBusMessage* structure can carry data payload, by appending boolean integers, real numbers, string etc. to the message body.
3. **D-Bus Path:** This is the path of a remote *Object* (capitalized to avoid ambiguity) of target process, e.g. `/org/freedesktop/DBus`.
4. **D-Bus Interface:** This is the interface on a given Object to talk with, e.g. `org.freedesktop.DBus`.
5. **D-Bus Method Call:** This is a type of D-Bus message that used to invoke a method on a remote Object.

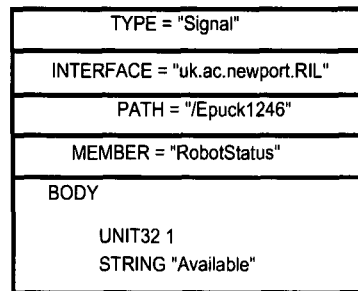


Figure 4.6: A typical structure of a D-Bus signal message.

6. **D-Bus Signal:** This is a type of D-Bus message to make a signal emission. Signal messages must have three header fields: D-Bus path and interface and *member* (exact signal name) giving the fully-qualified name of the signal. Fig. 4.6 shows the design of a robot-status signal that can be emitted over a specified interface and path with a data payload of an integer and a string containing the current status of a robot.
7. **D-Bus Error:** This is the structure that holds the error code which occurs by calling a D-Bus method.

Strategies for Application Integration

Under D-Bus, there are two basic mechanisms for applications to interact with each other: 1) by calling a remote Object of target application and 2) by emitting a signal for interested applications. To perform a method call on a D-Bus Object, a method call message must be sent to that Object. It will do some processing and return either a method return message or an error message. Signals are different in that they cannot return anything: there is neither a "signal return" message, nor any other type of error message⁸. Thus on D-Bus everything can be done asynchronously without the need of polling.

D-Bus provides several language bindings for integrating D-Bus to any native application. The core D-Bus API, written in C, is rather low-level and large. Bindings integrate with programming languages and environments, e.g. Glib, Python, Qt and Mono. The bindings provide environment-specific features. For example,

⁸<http://www.ibm.com/developerworks/linux/library/l-dbus.html>

the Glib bindings treat D-Bus connections as *GObjects* and allow messaging to integrate into the *Glib mainloop*. The preferred use of D-Bus is definitely using language and environment-specific bindings, both for ease of use and improved functionality (Love 2005).

4.2.3 BTCom/Myro: e-puck robot control programs

E-puck robot comes with a set of software tools and libraries to program and to monitor low-level sensor and actuator values. The low-level C library with driver code of e-puck robot can be downloaded from e-puck website⁹. In order to modify and recompile this library e-puck developers recommend both Windows and Linux cross-compiling tool-chains. Under Windows, the MPLAB environment from Microchip¹⁰ can be used with their C30 compiler. This commercial tool is used for programming e-puck robot (dsPIC micro-controller), since the Linux counterpart, piklab¹¹ has been found unstable and still under-development.

A wide variety of boot-loaders, both under Windows and Linux, can be used to upload the *.hex* firmware files to e-puck robot over Bluetooth. The trial version of Webots¹² simulator provides a most reliable e-puck boot-loader. E-puck website provides various other tools, e.g. Player robot control framework driver¹³ Matlab interfacing program, e-puck-monitor (under Windows) etc. for monitoring (or setting) sensors (or actuator) values. The default firmware running in e-puck robot is *BTCom*. It initializes Epuck robot hardware and waits for user command over Bluetooth serial port. A set of well-defined BTCom commands can be found in Epuck-library documentation.

For high-level control of e-puck robot, Myro robot-control framework¹⁴ is used that is developed by Institute for Personal Robots in Education. While BTCom provides a set of user commands for controlling the robot, it does not take care of the setting up the Bluetooth serial connection. Moreover the supplied user commands are very primitive in nature. For example, from a high-level perspective it is more desirable to command a robot for moving at a specific speed for a given time.

⁹www.e-puck.org

¹⁰<http://www.microchip.com>

¹¹<http://piklab.sourceforge.net/>

¹²<http://www.cyberbotics.com/products/webots/>

¹³<http://code.google.com/p/epuck-player-driver/>

¹⁴<http://wiki.roboteducation.org/>

Under BTCom, a user cannot achieve this without interactively giving low-level motor commands, e.g. set left/right motor speed. On the other hand, by setting up Myro framework, the Bluetooth communication with host PC and e-puck robot can easily be set-up under Python's pySerial¹⁵ module. This provides an elegant solution for controlling e-puck from software code. Besides, Myro provides a thin wrapper code for e-puck's BTCom for defining high-level user commands. For example, instead of setting left/right motor speed, a user can send a forward command with speed and time-out as its parameters. With the simplicity and interactivity of Python programming, this wrapper makes e-puck programming and debugging very simple and easy.

The default BTCom has another limitation that its detection of low battery voltage is almost unnoticeable by naked eye. For running a long time experiment this is critical since it is desired to continue experiments even if a few robots' batteries run out. By the default code of BTCom, a tiny red LED, located near the power LED in e-puck body, turns on when battery voltage becomes low. This LED light is not visible from a crowd of robots. In order to overcome this issue BTCom code is modified so that it can turn on all LEDs when battery voltage becomes critical. This exploited the hardware interrupt signal from Low-Voltage-Detection module of e-puck hardware.

Finally, custom navigation and obstacle avoidance algorithms are implemented. The navigation function is based on the camera pose information. In each time-step, robot gets its current pose information from the multi-robot tracking system. It then determines its current coordinate (location) relative to the target object and calculates the differences in pose and orientation. To advance forward, it at first corrects its heading based on the difference and then moves forward for a small fixed distance towards the target. Of course, in every time-step, it also checks that if it is located within the target object's boundary and if this is the case, it ceases its motion. Obstacle avoidance algorithm works under the navigation code. While a robot tries to move forward if an obstacle is sensed by its IR sensor it makes a random turn and tries to avoid it. Due to the noisy sensor values, it takes two or a few time-steps to completely get rid of that obstacle.

¹⁵<http://pyserial.sourceforge.net/>

4.2.4 BlueZ: Linux's Bluetooth communication stack

The physical communication between the host PC and e-puck robot occurs over Bluetooth wireless radio communication channel. As defined by the Bluetooth Special Interest Group's official technology info site¹⁶

"Bluetooth technology is a wireless communications technology intended to replace the cables connecting portable and/or fixed devices while maintaining high levels of security. The key features of Bluetooth technology are robustness, low power, and low cost".

The obvious reason for selecting Bluetooth as the communication technology of e-puck is perhaps due to its low cost, low battery usage and universality of hardware and software. Each e-puck robot has a Bluetooth radio link to connect to a host PC or nearby other e-puck robots. Under the hood, this Bluetooth chip, LMX9820A¹⁷, is interfaced with a Universal Asynchronous Receiver/Transmitter (UART) microchip of e-puck robot. This Bluetooth chip can be used to access to the UART "transparently" using a Bluetooth *rfcomm channel*. Using this mode, one can access the e-puck as if it is connected to a serial port. According to the specification of LMX9820A, it supports Bluetooth version 1.1 qualification. This means that the maximum supported data transfer speed is 1Mbit/s. But typically it is configured to use a serial port's 115200 bits/s speed.

Before starting to use an e-puck robot one needs to set-up the Bluetooth connection with the robot. Typical Bluetooth connection set-up from a Bluetooth-enabled host PC includes a few manual steps: detecting the remote Bluetooth device, securely bonding the device (e.g. exchanging secret keys) and setting-up the target *rfcomm* or serial connection (over radio) channel. Various Bluetooth software stacks are available under different OSes. Under Linux, BlueZ¹⁸ becomes the *de-facto* standard software platform. The BlueZ stack was initially developed by Max Krasnyansky at Qualcomm¹⁹ and in 2001 they decided to release it under the GPL.

The BlueZ kernel modules, libraries and utilities are known to be working perfect on many architectures supported by Linux. It offers full support for Bluetooth

¹⁶www.bluetooth.com

¹⁷<http://www.national.com/opf/LM/LMX9820A.html>

¹⁸www.bluez.org

¹⁹<http://www.qualcomm.com/>

device scanning, securely pairing with devices, rfcomm or serial link configuration, monitoring and so forth. Initial scanning and secure bonding of e-puck devices can be done by a set of BlueZ tools, namely, *hcitool*, *l2ping*, *hciconfig*, *rfcomm* etc. While initializing, BlueZ's core daemon, *bluetoothd*, reads the necessary configuration files (e.g. *rfcomm.conf*) and dynamically sets up or binds all Bluetooth devices' links and thereafter, routes all low-level communications to them. BlueZ's supplementary package, *Hcidump*, offers logging raw data of all Bluetooth communications over a host PC's Bluetooth adapter. In the host PC, USB dongle type Bluetooth adapters are used. Various Linux serial connectivity tools, e.g. *minicom*, *picocom* etc. are employed to test link configurations and to send BTCom commands to e-puck robots.

From the above points, it is seen that setting up and maintaining connectivity to e-puck robots through Bluetooth links is not a trivial task. Thus, one needs to consider automating the process of Bluetooth link set-up and verification in order to save time in initializing real experiments. Moreover, comparing with other common wireless technologies, e.g. Wifi, Bluetooth is a relatively low-bandwidth technology. In case of almost all wireless technologies, presence of lots of wireless devices causes significant noises and interferences. Thus, one also needs to consider the channel capacity or total available bandwidth for communications.

Within the context of MRTA experiments, an interesting open question has arisen. *What is the maximum number of e-puck robots that can talk to host PC simultaneously?* However, finding the answer of this question is beyond the scope of this thesis and here the author of this thesis has preferred to stick with the feasible configuration of Bluetooth links without modifying any low-level protocols or technical implementation.

4.2.5 Python's Multiprocessing: process-based multi-threading

The real-time interactions among multiple software applications often require concurrency and synchronization, to some degrees, in their functions. Although a common IPC protocol, e.g. D-Bus, solves the problem of data-sharing among different application processes, synchronization of data in various processes remains a challenging issue. The idea of simultaneous and parallel execution of different part of application codes without any IPC, typically on multiple CPU cores, introduces

the notion of *multi-threading* programming.

Both process-based and thread-based approach of program execution has pros and cons. Threads are light weight and they can share memory and state with the parent process without dealing with the complexity of IPC. Threads can be useful to the algorithms which rely on shared data/state. They can increase throughput by processing more information faster. They can also reduce latency and improve the responsiveness of an application, such as GUI actions. However, since threads implicitly “share everything” programmers have to protect (lock) anything which will be shared between threads. Thus thread-based programs are subject to face race conditions or deadlocks among multiple threads.

On the other hand, processes are independent process-of-control and they are isolated from each other by the OS. In order to do any data/state sharing they must use some form of IPC to communicate and coordinate. Comparing with threads, processes are big and heavy since process creation takes time and these processes also tend to be large in program size and memory footprint. Since processes “share nothing” – programmers must explicitly share any data/state with suitable mechanism. From a high-level robotic programmer’s point of view, both thread-based and process-based application design approaches are disadvantageous. Since thread-based approach requires careful attention in data-sharing it becomes very difficult to design bug-free program in short time-scale. On the other hand process-based approach requires to set-up IPC mechanisms and manage them. However, the latter approach is less likely to produce bugs as data sharing is explicit.

Almost all modern computer OSes and *high-level* programming languages, e.g. C/C++, Java etc. offer multi-threading support. However implementation of multi-threading programming involves lots of low-level thread management activities. In this respect *very high-level* programming languages e.g. Python, Ruby etc. offer more efficient and elegant solutions for dealing with multi-threaded programs. Along with this multi-threading issue, various other factors influence to use Python for coding high level robotic programs. For example, Python programs are usually optimized through *byte-codes* (like Java programs), and then they are *interpreted* by various Python interpreters. Unlike dealing with compiling issues in most of the high-level programming languages, Python allows programmers to focus on their algorithms more quickly and integrate their systems more effectively. Python’s in-

teractive program development process is found to be more productive and flexible than non-interactive programming approaches.

Starting from version 2.6, Python offers an integration of thread-based programming with process-based programming through its Multiprocessing module²⁰. Traditionally, Python offers threads that are real, OS/Kernel level POSIX *pthreads*. But, older Python programs can have only a single thread to be executing within the interpreter at once. This restriction is enforced by the so-called *Global Interpreter Lock* (GIL). This is a lock which must be acquired for a thread to enter the interpreter's space. This limits only one thread to be executing within the Python interpreter at once. This is enforced in order to keep interpreter maintenance easier.

But this can also be sidestepped if the application is I/O (e.g. file, socket) bound. A threaded application which makes heavy use of sockets, will not see a huge GIL penalty. After doing a lot of research on various alternatives of this approach, Python community has offered Multiprocessing as a feasible solution to side-step GIL by the CPU-bound applications that require seamless data/state sharing. It follows the threading API closely but uses processes and IPC under the hood. It also offers distributed-computing facilities as well, e.g. remote data-sharing and synchronization. Thus, the power and efficiency of Multiprocessing is exploited that enables to make a modular and flexible implementation of multi-robotic software system. Sec 4.3 explains some of the implementations of Python Multiprocessing module.

Python Multiprocessing offers various mechanisms for sharing data among processes or, more precisely speaking, among sub-processes. A separate *Manager* process is used that handles all the data storage tasks and event-based process synchronizations. Managers are responsible for network and process-based sharing of data between processes (and machines). The primary manager type is the *BaseManager* that is the basic Manager object, and can easily be subclassed to share data remotely. This Multiprocessing Manager object runs a server process in one machine and offers data objects through proxies in parallel to many client processes over network interfaces.

²⁰<http://docs.python.org/library/multiprocessing.html>

4.3 Multi-robot control architecture

Controlling a robot in a well-organized manner involves following a control architecture or a set of guiding principles and constraints. A control architecture organizes the structure of a robot's control software by defining the way in which sensing, reasoning and actions are represented, organized and interconnected (Bekey 2005). The overall aim of a multi-robot control architecture is to tie various necessary software components that enable a group of robots to work together and to achieve a common goal, such as self-regulated MRTA, by following a set of guiding principles and constraints.

Since this self-regulated MRTA solution closely follows the bio-inspired swarm robotic system's paradigm, simple e-puck robots are selected. Under this paradigm, distributed self-organized task-allocation approach (Chapter 5) is chosen that requires each robot to run its own task-allocation algorithm independently for selecting and switching among tasks (recall from Sec. 3.2 and Fig. 3.18). Robots need to gather task related information to run this task-allocation algorithm. Moreover, BTCom commands, that autonomously drive the robots, are also sent from a host PC's robot controller client program. Robots also need real-time pose data from multi-robot tracking system. All these requirements indicate that a suitable multi-robot control architecture is required that can effectively tie all these heterogeneous software components together.

In this Section, this question is answered by presenting a multi-robot control architecture, *hybrid event-driven architecture on D-Bus* (HEAD). As discussed in Sec. 4.2.2, this architecture uses D-Bus IPC mechanism for providing real-time, scalable, fault-tolerant and efficient interactions among various software components.

4.3.1 Hybrid event-driven architecture on D-Bus

As discussed in Sec. 3.1, robotic researchers have spent a lot of efforts for finding suitable robot control architecture. Since last few decades, robot control architectures have been evolving from deliberative to reactive and hybrid (combination of deliberative and reactive), behaviour-based and to some other forms. It has been well established that hybrid control can bring together the best aspects of both re-

active and deliberative control by combining the real-time low-level device control and high-level deliberative action control. Only reactive (or deliberative) control approach is not enough for enabling robots to do complex tasks in a dynamic environments (Gat et al. 1997).

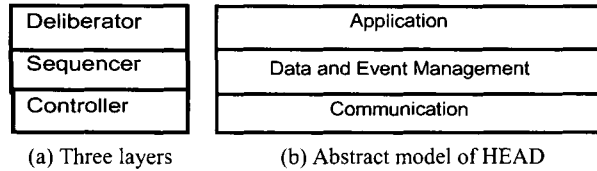


Figure 4.7: (a) Classical three-layer hybrid robot control architecture after Gat et al. (1997) (b) An abstract multi-robot control architecture adopted from hybrid architecture.

As shown in Fig. 4.7(a), hybrid control is usually achieved by a three-layer architecture composed of deliberator, sequencer and controller. *Controller* usually works under real-time reactive feedback control loops to do simple tasks by producing primitive robot behaviours, e.g. obstacle avoidance, wall following etc. *Deliberator* performs time-consuming computations, e.g. running exponential search or computer vision algorithm processing. In order to achieve specific task goals, the middle component, *sequencer*, typically integrates both deliberator and controller maintaining consistent, robust and timely robot behaviours.

Three layers of HEAD

In this study, the multi-robot control architecture HEAD is organized into three layers as shown in Fig. 4.7(b). Although HEAD has been designed by adopting the principles of hybrid architecture it has many distinct features that are absent or overlooked in a classical hybrid architecture.

Firstly, with respect to controller layer, HEAD broadly views sensing and control as communication with external entities. Communication as sensing is not new, e.g. it has been reported in multi-agent learning (Mataric 1998). When robots' on-board computing resources are limited communication can effectively make up their required sensing capabilities. On the other hand, low-level device control is also a series of communication acts where actuator commands are typically transmitted over a radio or physical link. Thus, all external communication takes place at the *communication layer*. Components sitting in this layer either act as sensors

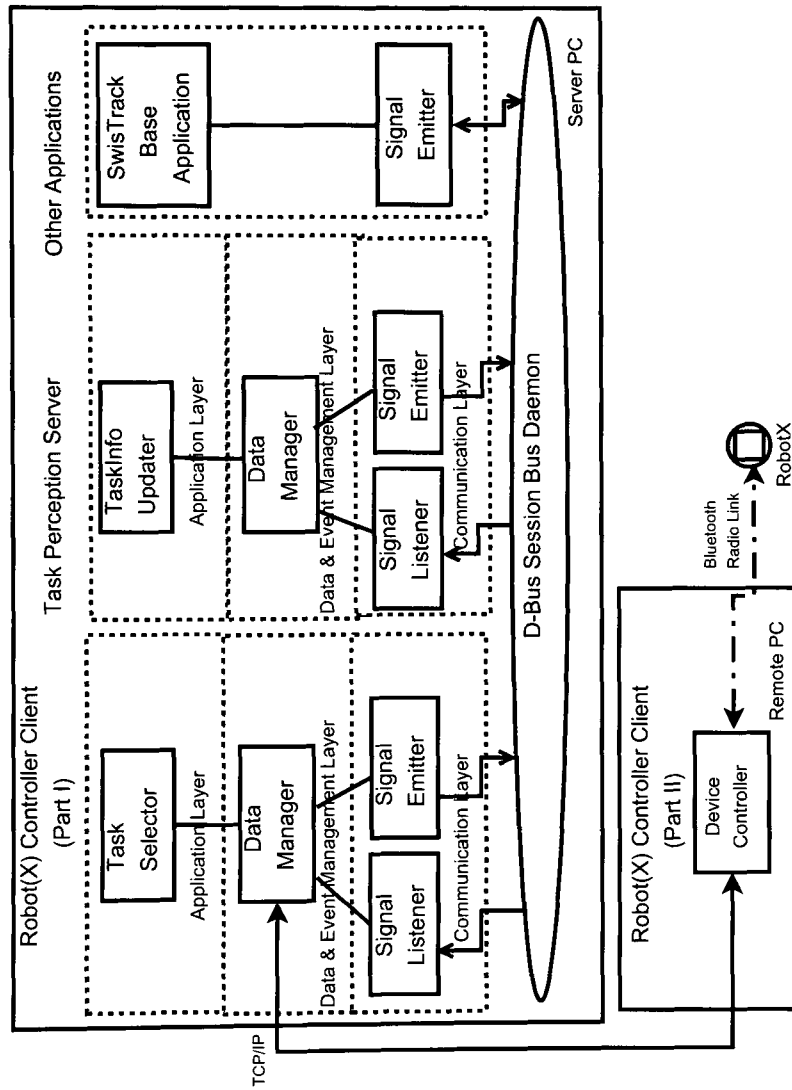


Figure 4.8: General outline of *HEAD*. A RCC application has been split into two parts: one runs locally in server PC and another runs remotely, e.g., in an embedded PC.

that can receive environmental state, task information, self pose data etc. via suitable communication link or do the real-time control of devices by sending actuator commands over a target communication channel. For example, in this study RCCs receive pose data from multi-robot tracking system through this communication layer.

Secondly, the apparent tight coupling with sensors to actuators has been reduced by introducing a *data and event management* (DEM) layer. DEM layer acts as a short-term storage of sensor data and various events posted by both controller and deliberator components. Task sequencing has been simplified by automated event triggering mechanism. DEM layer simply creates new event channels and components subscribe to their interested event channels for reading or writing. If one components updates an event, DEM layer notifies subscribed components about this event. Controller and deliberator components synchronize their tasks based on these event signals. DEM layer efficiently serves newly arrived data to the controller and deliberator components by this event sharing mechanism. For example, upon receiving robot pose data, RCCs save this data and notifies to other components about the availability of pose data so that they can do their work using this updated pose data. Thus unlike traditional hybrid architecture, neither specialized languages are needed to program a sequencer nor cumbersome if/else checks are present in this layer.

Lastly, deliberator layer of HEAD has been described as an *application layer* that runs real-application code based on high-level user algorithms as well as low-level sensor data and device states. For example, the self-regulated MRTA algorithms have been fitted in this layer. In classic hybrid architecture the role of this layer has been described mainly in two folds: 1) producing task plan and sending it to sequencer and 2) answering queries made by sequencer. Application layer of HEAD follows the former one by generating plan and queuing it to DEM layer, but it does not support the latter one. DEM layer never makes a query to an application since it acts only as a passive information gateway. Thus this reduced coupling between DEM layer and application layer has enhanced HEAD with additional robustness and scalability. Additional applications can be added with DEM layer's existing or new event interfaces. Any malfunction or failure in application layer or even in communication layer can be isolated without affecting others.

4.3.2 Software component integrations

Fig. 4.8 outlines the placements of various software components based on their functional characteristics and processing requirements. Here the integration of these software components in the communication layer of HEAD is discussed. The exact implementation of each of these components are left to be discussed in the following chapters within the specific context of MRTA applications. Note that, here the term *software component* or *application* is used to denote the logical groupings of several sub-processes or threads that works under a mother process or main thread (here the terms *thread* and *process* are used interchangeably).

Software components that follow this three-layer architecture for grouping its processes are called *native component* whereas existing software applications are called *external component*. As shown in Fig. 4.8, RCC and task-information provider, *task perception server* (TPS) are native software components of HEAD, whereas SwisTrack (Lochmatter et al. 2008), an external tool used with HEAD, is called an external component.

In order to integrate both native and external components with HEAD. Two separate communication processes are designed, i.e a D-Bus signal reception process, *SignalListener*, and a D-Bus signal emission process, *SignalEmitter*. Inside a native component both processes can communicate with data and event management process, *DataManager*, by using any suitable mechanisms, such as, multi-threading, multi-processing (offered in Python multiprocessing as discussed in Sec. 4.2.5), TCP or any other networking protocol.

Any external component that intend to act as a sensing (actuating) element of HEAD need to implement a *SignalEmitter* (*SignalListener*). For example, SwisTrack is extended with D-Bus signal emitting code (aka *SignalEmitter*) so that it can emit robot pose messages to individual robots D-Bus path under a common interface. This emitted signal is then caught by *SignalListener* of individual robot's RCC. Thus the tight-coupling between SwisTrack and RCC has been removed. During run-time SwisTrack can flexibly track variable number of robots and broadcast their corresponding pose messages without any re-compilation of code. Moreover, in worse cases, if SwisTrack or RCC crashes it does not affect any other component at run-time.

4.4 Summary

In this chapter the major methodological issues of multi-robot research have been discussed. The design of multi-robot system used in this study has been outlined here. The heterogeneous tools and technologies have been employed to set-up the necessary infrastructure for multi-robot experiments. A flexible multi-robot control architecture HEAD has been proposed and illustrated. The integration of various software components has been tackled in this architecture using the state-of-the-art D-Bus interprocess communication technology. In the following chapters, MRTA experiments have been implemented using this architecture.

Validation of Attractive Field Model for Self-regulated MRTA

In this chapter, AFM has been explained as an interdisciplinary model of self-regulated DOL in social systems. The model has been developed under the EPSRC collaborative project “Defying the rules how self-organizing systems work” (Arcaute et al. 2008). Here, three different social systems: ants, humans and robots have been studied in order to identify generic mechanisms that lead sustainability of social systems through self-regulation.

The construction of AFM has been achieved through a series of collaborative interactions among the EPSRC project partners¹. From the biological experiments of ants colonies *Temnothorax albipennis* the bottom-up rules have been inferred by examining the roles of feedback in collective performance of ants brood-sorting and nest construction after emigration to a new site. The observational data has been analysed from the self-organized infrastructural development of an *eco-village* by an open community of volunteers. These studies helped to formalize the generic rules into a concrete model and to validate this model by deploying it in robot controllers within the context of a manufacturing shop-floor scenario. In this chapter, the robotic validation of AFM has mainly been described with a brief presentation on interpretations of AFM from different social perspectives.

¹The partners of this project were from University of West of England, University of Hull, University of Wales, Newport and Imperial College London and they researched on ants, humans, robots and mathematical models respectively.

5.1 Motivations

The idea of finding a generic model of DOL, by collaboratively studying human, biological and artificial social systems, has many fascinating advantages. Below some of them have been presented.

Firstly, this interdisciplinary study makes it possible to develop a generic model of self-regulatory DOL by combining the strengths of different disciplines overcoming their individual shortcomings. For example, ant colonies are the ideal example for studying the self-regulatory social systems. However, it is very difficult to pin-point the exact mechanism leading to a specific behaviour. Artificial systems e.g. multi-robot system can be used to explore and verify biological hypotheses using totally controlled experiments. Similarly, observational data from human social systems can be combined with the data from the biological experiments to enhance the understanding of self-regulatory mechanisms in both of these social systems.

Secondly, synergy of different methods, and experimental and observational data from disparate disciplines, give the ability to construct a more abstract and powerful model which may not be available through independent studies. The higher-level abstraction can be very helpful to find the usefulness of this model since one can easily differentiate between generic and domain-specific components of the model. Generic part guides to design a core-framework that can be used to create basic characteristics of a system, whereas domain-specific part can be implemented independent of other disciplines. For example, different social systems use different communication mechanisms, yet almost all of them share many common aspects in their self-regulatory behaviours (Sec. 2.2).

Thirdly, the scope of application of generic models has been extended in many folds by tackling the common challenges of different disciplines. For example, both human social organizations and multi-robot systems suffer from the scalability issue for large organization. The properties of local sensing and local communication with relatively incapable sensory organs/hardware are present in both ants and swarm robotic systems. Thus, the integration of solutions from three major disciplines gives a highly flexible and extensible model of DOL.

5.2 The Attractive Field Model

The author of this thesis greatly acknowledge the contribution of the EPSRC project collaborators to formalize and document AFM. The text of this section has been taken from the project documents and informal communications with project members except Sec. 5.2.2 and Sec. 5.2.5 which are the author's own interpretations of AFM regarding self-regulation and robotic implementation.

5.2.1 Generic framework

Inspired from the DOL in ants, humans and robots, the following necessary and sufficient set of four requirements have been proposed for self-regulation in social systems.

Requirement 1: Concurrence The simultaneous presence of several options is necessary in order to meaningfully say that the system has organised into a recognisable structure. In task-allocation terms the minimum requirement is a single task as well as the option of not performing any task.

Requirement 2: Continuous flow of information Self-organised social systems establish a flow of information over the period of time when self-organisation can be defined. The task information provides the basis on which the agents self-organise by enabling them to perceive tasks and receive feedback on system performance.

Requirement 3: Sensitization The system must have a way of representing the structure produced by self-organisation, in terms of MRTA, which tasks the robots are allocated. One of the simplest ways of representing this information is an individual preference parameter for each task-robot combination. A system where each robot has different levels of preference or *sensitivity* to the available tasks, can be said to have to embody a distinct organisation through differentiation.

Requirement 4: Forgetting When a system self-organises by repeated increases in individual sensitisation levels, it is also necessary, in order to avoid saturation, to have a mechanism by which the sensitisation levels are reduced or *forgotten*. In addition to avoiding the situation where a structure produced by self-organisation is eroded by an eventual increase of sensitisation values to a given maximum, forgetting also allows flexibility in the system, in that the structure can

change as certain tasks become important and other tasks become less so. This effect can be achieved by mechanisms such as a slow general decay of sensitisation values or explicit negative feedback. Building on the requirements for self-organised social systems, AFM formalises these requirements in terms of the relationships between properties of individual agents and of the system as a whole (Arcaute et al. 2008). AFM is a bipartite network, i.e. there are two different types of nodes. One set of nodes describes the sources of the attractive fields, the tasks, and the other set describes the agents. Edges only exist between different types of nodes and they encode the strength of the attractive field as perceived by the agent. There are no edges between agent nodes. Communication among entities is considered as part of the attractive fields. There is also a permanent field representing the *no-task* option of not working in any of the available tasks. This option is modelled as a random walk.

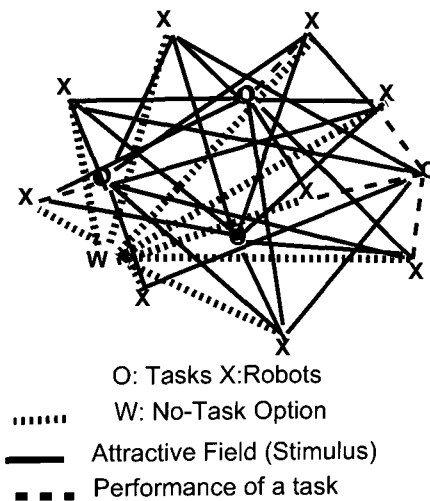


Figure 5.1: The attractive field model (AFM)

The model is presented graphically in Fig. 5.1. The elements depicted are:

1. Source nodes (o) are tasks to be allocated to agents
2. Agent nodes (x) e.g., ants, humans, or robots
3. Black solid edges represent the attractive fields and correspond to an agent's perceived stimuli from each task.

4. Green edges represent the attractive field of the ever present no-task option, represented as a particular task (w).
5. The black dashed lines are not edges, but represent how each agent is allocated to a single task at any point in time.

The edges of the AFM network are weighted and the value of this weight describes the strength of the stimulus as perceived by the agent. In a spatial representation of the model, the strength of the field depends on the physical distance of the agent to the source. In information-based models, the distance can represent an agent's level of understanding of that task. The strength of a field is increased through the sensitisation of the agent through experience with performing the task. This element is not depicted explicitly in Fig. 5.1 but is represented in the weights of the edges.

In Fig. 5.1, the nodes have arbitrary positions. Even though the distance is physical in this case, it need not be. When the model is applied to other domains, the distance can represent the accessibility of information or the time the information takes to reach the agent.

In summary, from the above diagram of the network, one can see that each of the agents is connected to each of the tasks. This means that even if an agent is currently involved in a task, the probability that it stops doing it in order to pursue a different task, or to random walk, is always non-zero.

5.2.2 Relationship of AFM with self-organization

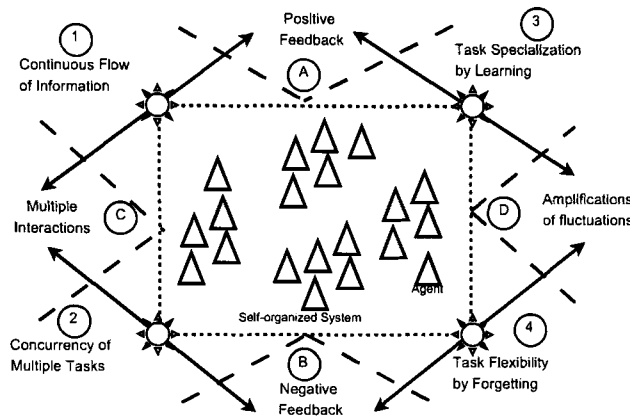


Figure 5.2: Four generic rules establish the self-regulated DOL in social systems

It is interesting to note that the proposed four generic rules can be considered as the four major foundations of a self-organized system (Fig. 5.2). As discussed in Sec. 2.1.1, self-organized systems exhibit four distinct perspectives known as so-called ingredients or properties of self-organization. However, it is not clear how those properties can come into existence. Here, the four underlying mechanisms have been described that explains how self-organization can be realized in different social systems using the generic framework of self-regulation. This can be explained in the following ways.

Firstly, multiple interactions become meaningful when *continuous flow of information* occurs by exchanging signals or cues among agents or their environment that regulates their behaviours. This, in turn, contribute to the task-allocation and task-switching in the social level. In swarm intelligence literature, multiple interactions are often described as an essential ingredient of self-organization. However, interactions without definite purposes may not contribute to the self-organization. Secondly, in swarm intelligence, positive feedback has been attributed as another mechanism of self-organization. But it is not easy to understand what creates positive feedback in a social system. Possible answers might be the characteristic of the environment e.g. ants select shorter path since density of pheromones become higher and thus more ants become attracted to that path, the gradual decrease of response-threshold of individuals which increases the probability of selecting a

task etc. To make the answer more concrete, *sensitization* or learning have explicitly been attributed as a mechanism of positive feedback. There might exist other mechanisms too. But clearly sensitisation will be one of the reliable mechanisms for achieving positive feedback.

Thirdly, similar to positive feedback, *forgetting* has been that contributes to provide negative feedback about a task or decreasing the probability to select it. Other negative feedback mechanisms can be implemented by assigning a saturation level to each task which is also present in AFM, for details see Arcaute et al. (2008).

Finally, creating artificial amplification of fluctuations or stochastic events is not a straight-forward issue. It throws many open questions. Does a system designer intentionally impose irregularity in task-performance of agents? Is random movement enough for simulating randomness in a system? Since emergencies do not always pop-up on request, the rule of *concurrency* enables agents to maintain even a small amount of probability of selecting a low-priority, or less sensitized or distant task. This concurrency mechanism provides a high-degree of robustness in the system such that all tasks can be attended even if specialization of agents delays them in switching to some of the tasks.

5.2.3 Interpretation of AFM in ant colonies

The interpretation of AFM in an ant colony almost exactly follows the above generic interpretation. For ants it is assumed that DOL is not genetically driven. Initially they are all equal. It is not fully understood how ants “know” or get information about tasks. But they all interact directly and indirectly and perform tasks. The flow of information can take place in many different ways. As discussed in Sec. 2.2, ants can get information through direct P2P, local or global broadcast and indirect pheromone communications. In any case, if an ant i_1 is closer to the source of information, i.e. task, than any other ant i_2 , there will be larger probability that i_1 will get that information than i_2 . If all ants are assumed to be initially equal it will be more likely that i_1 will attend to that task. Thus each task can be treated as an attractive source, stimulating ants to go to it. Here the stimulus primarily depends on the distance.

In case of sensitization or learning, an ant that has performed a task, it is assumed that it will be more likely that it will be attracted to do it again. Here there is

no encoding of individual performance, the specialists are more attracted towards the task but do not perform the task quicker than other ants. Thus the performance of colony increases as a result of sensitisation. Simultaneity (concurrency) of tasks over period of time of self-regulation can also be achieved through spatial dependence of strength of stimulus. Some ants will be favoured to get information from multiple sources than others. When an ant does not do a task for relatively long time it is less probable that it will do that task again. This will lead to forgetting of their tasks gradually. Flexibility in task switching is achieved through this forgetting of tasks. A concrete interpretation of AFM in an ant colony, along with simulation results can be found in Arcaute et al. (2008).

5.2.4 Interpretation of AFM in human societies

The interpretation of AFM in a human society can be made using many different approaches. For example, using Fig. 5.1 the following can re-interpret the mappings of different nodes and characteristics of AFM for a human society.

- Source nodes (o) can be resources (or tasks).
- Agents (x) can be people.
- The links can correspond to the flow of information about resources (or tasks) among people.
- The distance dependence can be introduced here in the same way as with the ants. People working in a certain area are more likely to receive information of resources with respect to that area, than another person doing something else. How a person uses that information, corresponds to that person's ability to contribute towards a given goal. The weight of the link is the amount of information a person can get. The person can use it or dismiss it. Random walking would correspond to dismiss it. AFM does not differentiate between good and bad information. It is always considered as good information.

Similar to the above biological interpretation, one can find that in human society the DOL can also be interpreted in terms of AFM. People can get information about certain tasks or resources from various sources. Those who are located near the source of information are more likely to attend it, e.g. through the access

to Internet, some people can get information quicker than others. This can be treated as the distance to tasks or resources. The motivation of a person to use information can also be treated as the distance in the model. The background training, education or skill profile can be used to estimate the sensitization to do a task or use a resource. The urgency of a task can be inferred through some other estimates, e.g. the frequency of mentioning about a task, by team members or peers.

5.2.5 Interpretation of AFM in multi-robot systems

The interpretation of AFM in a multi-robot system also follows almost exactly as in generic interpretation. However, in order to make the interpretation more concrete, let it be a manufacturing shop floor scenario, where N number of autonomous mobile robots are required to attend J number of shop tasks spread over a fixed area A . Let these tasks be represented by a set of small rectangular boxes resembling manufacturing machines.

Let R be the set of robots r_1, r_2, \dots, r_n . Let a task j that has an associated task-urgency ϕ_j indicating its relative importance over time. If a robot attends a task j in the x^{th} time-step, the value of ϕ_j will decrease by an amount $\delta_{\phi_{DEC}}$ in the $(x + 1)^{th}$ time-step. On the other hand, if a task has not been served by any robot in the x^{th} time-step, ϕ_j will increase by another amount $\delta_{\phi_{INC}}$ in $(x + 1)^{th}$ time-step. Thus urgency of a task is updated by the following rules.

$$\text{If the task is not being done : } \phi_j \rightarrow \phi_j + \delta_{\phi_{INC}} \quad (5.1)$$

$$\text{If the task is being done : } \phi_j \rightarrow \phi_j - n \delta_{\phi_{DEC}} \quad (5.2)$$

Eq. 5.1 refers to a case where no robot attends to task j and Eq. 5.2 refers to another case where n robots are concurrently performing the task j .

In order to complete a task j , a robot r_i needs to be within a fixed boundary D_j . If a robot completes a task j it learns about it and this will influence r_i 's likelihood of selecting that task in future, say through increasing its sensitization to j by a small amount, k_{INC} . Here, the variable affinity of a robot r_i to task j is called as its *sensitization* k_j^i . If a robot i does not do a task j for some time, it forgets

about j and k_j^i is decreased, by another small amount, say k_{DEC} . Thus a robot's task-sensitization update follows these rules.

$$\text{If task is done : } k_j^i \rightarrow k_j^i + k_{INC} \quad (5.3)$$

$$\text{If task is not done : } k_j^i \rightarrow k_j^i - k_{DEC} \quad (5.4)$$

According to AFM, all robots will establish attractive fields to all tasks due to the presence of a system-wide continuous flow of information. The strength of these attractive fields will vary according to the dynamic distances between robots and tasks, task-urgencies and corresponding sensitizations of robots. Simplifying the generic implementation of AFM from Arcaute et al. (2008), this stimuli of attractive field can formally be encoded as follows.

$$S_j^i = \tanh\left\{\frac{k_j^i}{d_{ij} + \delta}\phi_j\right\} \quad (5.5)$$

$$S_{RW}^i = \tanh\left\{1 - \frac{\sum_{j=1}^J S_j^i}{J+1}\right\} \quad (5.6)$$

$$P_j^i = \frac{S_j^i}{\sum_{j=0}^J S_j^i} \text{ where, } S_0^i = S_{RW}^i \quad (5.7)$$

Eq. 5.5 states that the stimuli of a robot r_i to a particular task j , S_j^i depends on r_i 's spatial distance to j (d_{ij}), level of sensitization to j (k_j^i), and perceived urgency of that task (ϕ_j). In Eq. 5.5, a very small constant value δ is used to avoid division by zero, in the case when a robot has reached to a task. Since S_j^i is a probability function, it is chosen as a \tanh in order to keep the values between 0 and 1. Eq. 5.6 suggests how one can estimate the stimuli of random walk or no-task option. This stimuli of random walk depends on the sum of stimulus of J real tasks. Here, random-walk is also considered as a task. Thus the total number of tasks become $J+1$. The probability of selecting each task has been determined by a probabilistic method outlined in Eq. 5.7 which states that the probability of choosing a task j by robot r_i is directly proportional to its calculated stimuli S_j^i . Finally, let T_a be the allocated time to accomplish a task. If a robot can enter inside the task boundary within T_a time it waits there until T_a elapsed. Otherwise it will select a different task.

5.3 A manufacturing shop-floor scenario

By extending the interpretation of AFM in multi-robot system, one can set-up manufacturing shop-floor scenario. Here, each task represents a manufacturing machine that is capable of producing goods from raw materials, but they also require constant maintenance works for stable operations. Let W_j be a finite number of material parts that can be loaded into a machine j in the beginning of its production process and in each time-step, ω_j units of material parts can be processed ($\omega_j \ll W_j$). So let Ω_j^p be the initial production workload of j which is simply: W_j/ω_j unit.

It is assumed that all machines are identical. In each time step, each machine always requires a minimum threshold number of robots, called hereafter as *minimum robots per machine* (μ), to meet its constant maintenance work-load, Ω_j^m unit. However, if μ or more robots are present in a machine for production purpose, it is assumed that no extra robot is required to do its maintenance work separately. These robots, along with their production jobs, can do necessary maintenance works concurrently. For the sake of simplicity, the value of μ can be assumed as 1.

Now the above production and maintenance work-loads and task performance of robots need to be converted into a unit task-urgency scale. The manufacturing operation can be divided into two subsequent stages: 1) *production and maintenance mode* (PMM), and 2) *maintenance only mode* (MOM). Initially a machine starts working in PMM and does production and maintenance works concurrently. When there is no production work left, then it enters into MOM.

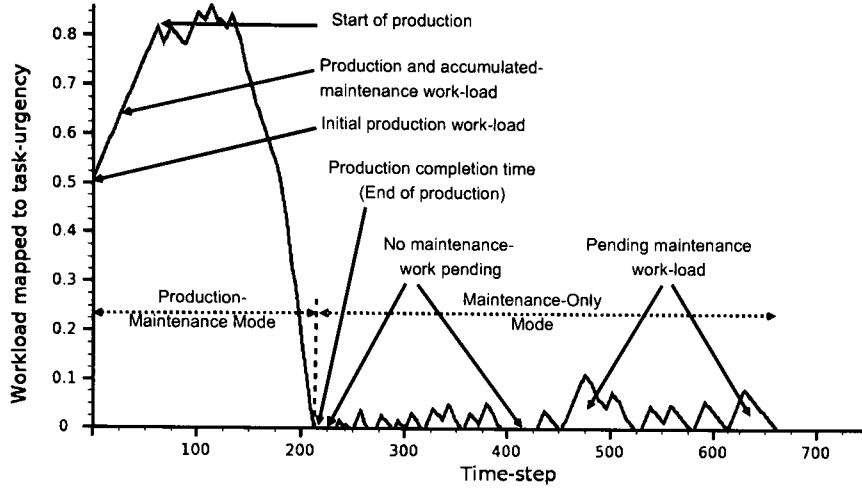


Figure 5.3: A manufacturing shop-floor production and maintenance cycle

Fig. 5.3 illustrates this scenario for a single machine. Under both modes, let α_j be the amount of workload occurs in a unit time-step if no robot serves a task and it corresponds to a fixed task-urgency $\Delta\phi_{INC}$. On the other hand, it is assumed that in each time-step, a robot, i , can decrease a constant workload β_i by doing some maintenance work along with doing any available production work. This corresponds to a negative task urgency: $-\Delta\phi_{DEC}$. So, at the beginning of production process, task-urgency, occurred in a machine due to its production work-loads, can be encoded by Eq. 5.8.

$$\Phi_{j,INIT}^{PMM} = \Omega_j^p \times \Delta\phi_{INC} + \phi_j^{m0} \quad (5.8)$$

where ϕ_j^{m0} represents the task-urgency due to any initial maintenance work-load of j . Now if no robot attends to serve a machine, each time-step a constant maintenance workload of α_j^m will be added to j and that will increase its task-urgency by $\Delta\phi_{INC}$. So, if k time steps passes without any production work being done, task urgency at k^{th} time-step will follow Eq. 5.9.

$$\Phi_{j,k}^{PMM} = \Phi_{j,INIT}^{PMM} + k \times \Delta\phi_{INC} \quad (5.9)$$

However, if a robot attends to a machine and does some production works from it, there would be no extra maintenance work as it is assumed that $\mu = 1$. Rather, the task-urgency on this machine will decrease by $\Delta\phi_{DEC}$ amount. If ν_k robots work

on a machine simultaneously at time-step k , this decrease will be: $\nu_k \times \Delta\phi_{DEC}$. So in such cases, task-urgency in $(k + 1)^{th}$ time-step can be represented by:

$$\Phi_{j,k+1}^{PMM} = \Phi_{j,k}^{PMM} - \nu_k \times \Delta\phi_{DEC} \quad (5.10)$$

At a particular machine j , once $\Phi_{j,k}^{PMM}$ reaches to zero, it can be said that there is no more production work left and this time-step k can give the *production completion time* of j , T_j^{PMM} . Average production time-steps of a shop-floor with M machines can be calculated by the following simple equation.

$$T_{avg}^{PMM} = \frac{1}{M} \sum_{j=1}^M T_j^{PMM} \quad (5.11)$$

T_{avg}^{PMM} can be compared with the minimum number of time-steps necessary to finish production works, T_{min}^{PMM} . This can only happen in an ideal case where all robots work for production without any random walking or failure. One can get T_{min}^{PMM} from the total amount of work load and maximum possible inputs from all robots. If there are M machines and N robots, each machine has Φ_{INIT}^{PMM} task-urgency, and each time-step robots can decrease $N \times \Delta\phi_{DEC}$ task-urgencies, then the theoretical T_{min}^{PMM} can be found from the following Eq. 5.12.

$$T_{min}^{PMM} = \frac{M \times \Phi_{INIT}^{PMM}}{N \times \Delta\phi_{DEC}} \quad (5.12)$$

$$\zeta_{avg}^{PMM} = \frac{T_{avg}^{PMM} - T_{min}^{PMM}}{T_{min}^{PMM}} \quad (5.13)$$

Thus one can define ζ_{avg}^{PMM} , average production completion delay (APCD) by following Eq. 5.13, When a machine enters into MOM, only μ robots are required to do its maintenance works in each time step. So, in such cases, if no robot serves a machine, the growth of task-urgency will follow Eq. 5.9. However, if ν_k robots are serving this machine at a particular time-step k^{th} , task-urgency at $(k + 1)^{th}$ time-step can be represented by:

$$\Phi_{j,k+1}^{MOM} = \Phi_{j,k}^{MOM} - (\nu_k - \mu) \times \Delta\phi_{DEC} \quad (5.14)$$

By considering $\mu = 1$, Eq. 5.14 will reduces to Eq. 5.10. Here, $\Phi_{j,k+1}^{MOM}$ will correspond to the *pending maintenance work-load* of a particular machine at a

given time. This happens due to the random task switching of robots with a no-task option (random-walking). Interestingly PMW will indicate the robustness of this system since higher PMW value will indicate the delay in attending maintenance works by robots. One can find the *average pending maintenance workload* (APMW) per time-step per machine, χ_j^{MOM} (Eq. 5.15) and average PMW per machine per time-step, χ_{avg}^{MOM} (Eq. 5.16).

$$\chi_j^{MOM} = \frac{1}{K} \sum_{k=1}^K \Phi_{j,k}^{MOM} \quad (5.15)$$

$$\chi_{avg}^{MOM} = \frac{1}{M} \sum_{j=1}^M \chi_j^{MOM} \quad (5.16)$$

5.4 Experiment design

A set of manufacturing shop-floor scenario experiments have been designed for validating the effectiveness of AFM in producing self-regulated MRTA. The overall aim of this design is to analyse the various properties of task-allocation and related other issues. In this section, the design of the observables and parameters of the experiments have been described within the context of a manufacturing shop-floor scenario.

5.4.1 Observables

Plasticity: As discussed in Sec. 2.1.3, self-regulated DOL can be characterised by plasticity and task-specialization, in both macroscopic and microscopic levels. Within manufacturing shop-floor context, plasticity refers to the collective ability of the robots to switch from doing no-task option (random-walking) to doing a task (or vice-versa) depending on the work-load present in the system. Here one can expect to see that most of the robots would be able to engage in tasks when there would be high workloads (or task-urgencies) during PMM. Similarly, when there would be low workload in case of MOM only a few robots would do the task, rest of them would either be idle (not doing any task) or perform a random-walk. The changes of task-urgencies and the ratio of robots engaged in tasks can be good metrics to observe plasticity in MRTA.

Task-specialization: Under heavy work-load most of the robots should attend to tasks. But self-regulated DOL is always accompanied with task-specializations of agents. That means that a few robots will be more active than others. From AFM, one can see that after doing a task a few times, a robot will soon be sensitized to it. Therefore, from the raw log of task-sensitization of robots, one can be able to find the pattern of task-sensitization of robots per task basis. If a few robots specialize on a particular task that will help to reduce traffic near the task and improves overall efficiency of the system. Thus, at the end of the production cycle in manufacturing shop-floor scenario, one can count the percentage of robots specialized on each task in the experiments.

Quality of task-performance: As discussed in Sec. 5.3 one can measure the quality of MRTA from the APCD. It first calculates the ideal minimum production time and then finds the delay in production process from the actual production completion data. Thus this will indicate how much more time is spent in the production process due to the self-regulation of robots in this distributed task-allocation scheme. In order to calculate APCD, one can find the production completion time for each task from the raw log of task-urgency and make an average from them.

Robustness: In order to see if the system can respond to the gradually increasing workloads, one can measure APMW within the context of the manufacturing shop-floor scenario. This can show the robustness of a system where a task can be unattended for long time. When a task is not being served by any robot for some time, one can see that its urgency will rise and robots will respond to this dynamic demand. For measuring APMW only the task-urgency data is needed.

Flexibility: From the design of AFM, it is known that robots that are not doing a task will be de-sensitized to it or forget that task. So at an overall low work-load (or task urgency), less robots will do the tasks and hence less robots will have the opportunity to learn tasks. From the shop-floor work-load data, it can be confirmed the presence of flexibility in MRTA.

Energy-efficiency: In order to characterize the energy-efficiency in MRTA the pose data of each robot can be logged that can give the total translations occurred by all robots in MRTA experiments. This can give a rough indication of energy-usage by the robots.

Information flow: Since AFM requires a system-wide continuous flow of informa-

tion, one can measure the communication load to bench-mark the implementation of communication system. This bench-mark data can be used to compare among various communication strategies. Here one can measure how much task-related information, i.e. task-urgency, location etc. are sent to the robots at each time step. This amount of information or communication load can be constant or variable depending on the design of the communication system.

Scalability: In order to see the effects of scaling on MRTA, two series of experiments have been designed. *Series A* corresponds to a small group where 8 robots are used for 2 tasks under an arena of 2 m^2 . The numbers have been doubled in *Series B*, i.e. 16 robots, 4 tasks under an arena of 4 m^2 . This proportional design can give a valuable insight about the effects of scaling on self-regulated MRTA. All of the above metrics of Set A and Set B can be compared to find those scalability effects.

Thus, in order to observe the above properties of self-regulated MRTA, the following observables have been recorded in each time-step.

1. Task-urgency of each task (ϕ).
2. Number of robots engaged in each task.
3. Task-sensitizations (k) of robots.
4. Pose data of robots.
5. Communication of task-information message with robots.

5.4.2 Parameters

Table 5.1 lists a set of essential parameters of the experiments. A relatively complex environment has been set-up, i.e., a high number of robots and tasks in a large area. The diameter of the marker of e-puck robot is 0.08m. So, if 4 robots are put in an area of one square meter, this will give a robot-occupied-space to free-space ratio of about 1:49 per square meter. This ratio is reasonable in order to allow the robots to move at a speed of 5 cm/sec without much interference to each other.

The initial values of task urgencies correspond to 100 units of production work-load without any maintenance work-load as outlined in Eq. 5.8. A limit of 0 and 1

Table 5.1: Experimental parameters of Series A & B experiments

Parameter	Series A	Series B
Total number of robots (N)	8	16
Total number of tasks (M)	2	4
Experiment area (A)	2 m^2	4 m^2
Initial production work-load/machine (Ω_i^p)	100 unit	
Task urgency increase rate ($\Delta\phi_{INC}$)	0.005	
Task urgency decrease rate ($\Delta\phi_{DEC}$)	0.0025	
Initial sensitization (K_{INIT})	0.1	
Sensitization increase rate (Δk_{INC})	0.03	
Sensitization decrease rate (Δk_{DEC})	0.01	

is chosen, where 0 means no urgency and 1 means maximum urgency. Same rule applies to sensitisation, where 0 means no sensitisation and 1 means maximum sensitisation. This also implies that if sensitization is 0, task has been forgotten completely. On the other hand, if sensitization is 1, the task has been learnt completely. A default sensitization value of 0.1 has been selected for all tasks. The following relationships are maintained for selecting task-urgency and sensitization parameters.

$$\Delta\phi_{INC} = \frac{\Delta\phi_{DEC} \times N}{2 \times M} \quad (5.17)$$

$$\Delta k_{DEC} = \frac{\Delta k_{INC}}{M - 1} \quad (5.18)$$

Eq. 5.17 establishes the fact that task urgency will increase at a higher rate than that of its decrease. In order to keep a task left unattended for a long time a higher rate of increase of task urgency has been chosen. This difference is set on the basis of the assumption that at least half of the expected number of robots (ratio of number of robots to tasks) would be available to work on a task. So they would produce similar types of increase and decrease behaviours in task urgencies.

Eq. 5.18 suggests that the learning will happen much faster than the forgetting. The difference in these two rates is based on the fact that faster learning gives a robot more chances to select a task in next time-step and thus it becomes more specialized on it.

5.5 Implementation

Ideally, AFM can be implemented as a complete distributed task-allocation system where each agent selects its own task based on its own external perception about task-urgencies (i.e. attractive fields), distances from tasks and internal task-sensitisation records. Such an implementation requires powerful robots with sophisticated sensors (camera, laser etc.) and sufficient computation and communication capabilities. In that case, robots can keep task-urgency information up-to-date through suitable local communication schemes with their peers who can monitor the tasks. By using suitable navigation and mapping modules, they can also accurately calculate the distances from tasks and navigate to tasks autonomously. Moreover, they also require necessary hardware to do the actual task, e.g. gripper for pick-up tasks.

However, this study has been undertaken to find the suitable communication schemes that can effectively spread the attractive fields (task-urgencies) among robots. So the complexities of a full-fledged implementation have been simplified by using a centralized communication system that effectively makes up the limitations of e-puck robots. For example, these robots are not capable of sensing a task to estimate its urgencies, instead a centralized *task-perception server (TPS)* broadcast task information, e.g. task-urgencies, locations etc. to robots in certain time intervals. Within this interval, if some robots work on a task, they independently send their status, i.e. which task they are currently doing. From this status message, TPS can re-calculate the task-urgencies and send them in next broadcast.

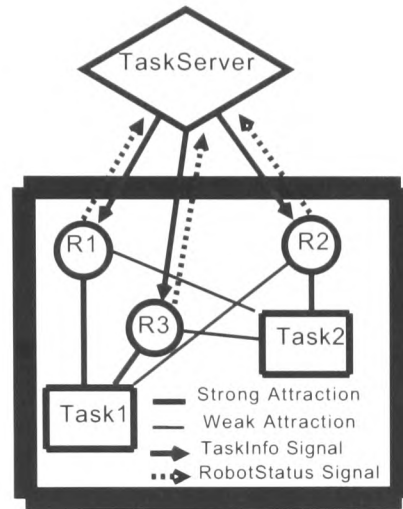


Figure 5.4: A centralized communication scheme

Fig. 5.4 shows how three robots are attracted to two different tasks and their communications with TPS. Here although the robots are selecting task independently based-on the strength of their attractive fields to different tasks, they are depended on the TPS for task-information.

This centralized communication system can be converted into a decentralized one where robots can use local observation and communication with peers about tasks to estimate task-urgencies. In Chapter 6, an emulation of this scenario is presented where robots do not depend entirely on TPS for estimating task-urgencies, instead they get task information from TPS when they are very close to a task (inside a pre-defined task-boundary) or from local peers who know about a task via TPS.

In this implementation, instead of doing any real work with powerful robots, a mock manufacturing shop-floor scenario has been emulated that requires the robot only to travel among tasks. As discussed in Sec. 4.2.3, e-puck robots do not have on-board CPU, they need a host PC to control them using BTCom communication protocol. Thus the host-PC runs one RCC for each physical robot. These RCCs also rely upon SwisTrack multi-robot tracking system for updating their real-time pose. So although AFM based MRTA solution is distributed by design, a centralized approach has been used to implement it due to the limitations of e-puck

robots and the convenience of implementation. Below the actual implementations of these components is described, such as D-Bus communication interfaces and detail implementations of TPS and RCC.

5.5.1 D-Bus communication interfaces

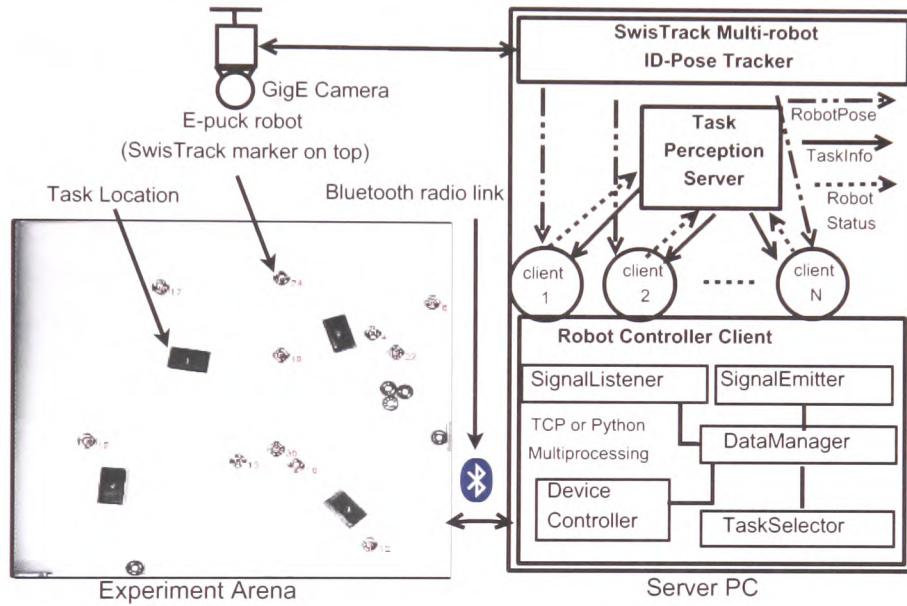


Figure 5.5: Hardware and software setup for series A & B experiments

A centralized communication system interfaces among SwisTrack, TPS and RCC as shown in Fig. 5.5. The communication protocol is based on D-Bus IPC. As discussed in Sec. 4.2.2, each message is a D-Bus signal (similar to Fig. 4.6). The characteristics of these messages are discussed below.

RobotPose: SwisTrack emits this D-Bus signal and its payload contains individual robot's pose data: robot-pose x-coordinate, y-coordinate and robot orientation (theta). The type of each data is DBUS_TYPE_DOUBLE (IEEE 754 double). In this study SwisTrack has been extended by adding a D-Bus signal emitter module which emits this signal in every image-processing cycle. The typical duration of each cycle varies from 1 to 2 seconds. SwisTrack extracts robot-pose from the image frame considering top-left corner of image as origin and it derives theta from the relative position of the monochrome robot-marker from the image. SwisTrack's

id-pose detection algorithms handles the complexities of finding the accurate robot-pose. RobotPose signal is sent to RCC using robot-id based separate D-Bus paths. e.g. /robot1, /robot2 etc. But all RobotPose signals are emitted in same D-Bus interface `uk.ac.newport.ril.SwisTrack`. In order to get pose data, each RCC filters this D-Bus signal using this interface and self-id based path.

TaskInfo: TPS emits this signal after a fixed time intervals. The payload of this message contains an array of all task's information. Each element of the array contains a task's: task-id, Time-stamp, pose x, pose y, task-urgency (ϕ). Task-id data is integer type and all others are double. Time-stamp in data ensures using up-to-date task information since RCCs receive TaskInfo from TPS asynchronously. If the tasks are dynamic their pose can be obtained from SwisTrack as well. In this implementation, static pose data have been provided to all task as an argument to TPS module. So the dynamic part, i.e. the time-stamp and up-to-date task-urgency is determined by the task-information-updater module of TPS, according to Algorithm 4.1. This D-Bus signal is sent in a common D-Bus interface, `uk.ac.newport.ril.TaskServer`, under path, /taskserver. Each RCC receives this message by listening to this interface and path.

RobotStatus: Each RCC emits this D-Bus signal and the payload contains: individual robot's id and its currently executing task's id. This message is sent to a common D-Bus interface `uk.ac.newport.ril.Epuck` and path /robot. But TPS identifies the sender from the message pay-load, i.e. robot-id. A RCC emits this signal only when it starts working on a particular task.

5.5.2 Robot-controller client

As shown in Fig. 5.5, each e-puck robot is controlled by a corresponding RCC. An RCC sends commands to the robot's firmware using BTCom protocol (Sec. 4.2.3). An RCC consists of several Python modules. Each module represents a sub-process under a main process that ties all of them together by using Python's Multiprocessing module. Below the detail design and implementation of these Python modules have been described. All code are publicly accessible through GitHub repository².

²[git://@github.com/roboshepherd/EpuckCentralizedClient.git](https://github.com/roboshepherd/EpuckCentralizedClient.git), hash: 7e3af8902e64db3fa59e

Table 5.2: Data structures and events used by the RCC

Data structure	Related event(s)
mRobotID	-
mRobotPose	mRobotPoseAvailable
mTaskInfo	mTaskInfoAvailable
mSelectedTask	mSelectedTaskAvailable mSelectedTaskStarted mTaskTimedOut

DataManager

As discussed in Sec. 4.2.5, under a process-based design of IPC among multiple processes, a programmer needs to specify explicitly which data and states should be shared among sub-processes. According to the design of the multi-robot control architecture, HEAD (Sec. 4.3), a data and event management process called *DataManager* have been employed that acts as a data warehouse and event management centre for RCC.

Table 5.2 lists the major data structures and corresponding event channels of *Data Manager*. Here *mRobotID*, an integer type data, represents the e-puck robot's marker ID (converted to decimal number from the binary code) which uniquely identifies a robot from others. This is given as a command-line argument during RCC start-up. Python *dictionary* type data structure have been used for all other data structures that are managed by the Python Multiprocessing's *Manager()* object. Any other process e.g. *TaskSelector*, can access *DataManager*'s data and event channels locally by taking a reference of *DataManager* object from the Multiprocessing's parent process. *DataManager* object also runs a tiny TCP/IP server process powered by the Multiprocessing's *RemoteManager()* interface. So, if necessary, any other process e.g. *DeviceController*, can access all of the *DataManger*'s data structures and event channels remotely by instantiating a proxy client that connects to this embedded TCP/IP server of *DataManager* and fetch data from it. In the following paragraphs, under the discussion of other RCC processes, the update process of rest of the data structures and event channels are explained.

SignalListener

As mentioned in Sec. 4.3.2, two D-Bus communication modules in RCC: `SignalListener` and `SignalEmitter` have been employed that are responsible for listening and emitting D-Bus signals respectively. `SignalListener`, has subscribed to D-Bus session bus for listening to D-Bus `RobotPose` and `TaskInfo` signals that are discussed above. `SignalListener` uses two callback functions that handles both of these signal reception events. For example when `SwisTrack` emits `RobotPose` signal the corresponding handler function becomes activated and receive this `RobotPose` signal's payload data (i.e. `x`, `y`, `theta`). It then makes a copy of these data to `DataManager`'s `mRobotPose` data structure and label them as dictionary key/value pairs, where `x`, `y`, `theta` etc. becomes the dictionary keys. In addition to copying the data, `SignalListener` also set the `DataMager`'s `mRobotPoseAvailable` event to `True`. In consequence, those processes that are waiting for `mRobotPose` data, e.g. `TaskSelector`, finishes their waiting and try to access this newly arrived `mRobotPose` data. After reading to this data they mark this `mRobotPoseAvailable` event as `False` so that this pose data can be treated as outdated and waiting processes can wait for new pose update. This strategy ensures the consistent and real-time data read/write by all subscribing processes.

SignalEmitter

Similar to the `SignalListener`, `SignalEmitter` makes use of Python `sched` module that enables it to check periodically `mSelectedTaskStarted` event and emit a robot's task status containing signal, `RobotStatus`. This is done by subscribing to the `mSelectedTaskStarted` event channel. When a robot executes a task, this event channel becomes activated by `DeviceController` (discussed below).

At a very close time, `SignalEmitter` gets this event update and finishes waiting for this event. It then picks up the `mSelectedTask` data from `DataManager` and prepare the `RobotStatus` signal and emits it to the session bus. Upon a successful emission event, it clears `mSelected TaskStarted` event so that only one `RobotStatus` signal is emitted per task-cycle.

TaskSelector

TaskSelector works in the application layer of multi-robot control architecture, HEAD. It plugs the AFM algorithms into RCC to select task based-on DataManager's event notifications, i.e. mRobotPoseAvailable and mTaskInfoAvailable and upon running task-allocation algorithm it updates mSelectedTask (and mSelectedTaskAvailable) with selected task information.

TaskSelector allocates a robot with a shop-task or random-walk task from several inputs: as shown in Algorithm 4.1. Here *AllTaskInfo* and *RobotPose* correspond to the mTaskInfo and mRobotPose of DataManager. *TaskRecords* is a dictionary type data structure that keeps track of related calculations, e.g. stimulus, of all tasks. This is internally maintained by the TaskSelector process. *DeltaDistance* is a very small constant number to avoid division by zero in calculating task stimuli, as mentioned in Eq. 5.5.

Task-allocation algorithm:

Stage 1. During the initialization of the task-allocation algorithm, the total number of tasks has been counted and initialize the sum of the stimuli all tasks to zero. Then for each task, its pose, urgency, sensitisation are extracted from input data. *CalculateTaskDistance()* function calculates the Euclidian distance between a task and a robot by taking the current robot-pose and static task-pose as the input. These values are enough to get a task's stimuli based on Eq. 5.5. In this loop finally *TaskRecords* is updated for using it in next task-allocation cycle. The random-walk task's stimuli is found from Eq. 5.6. It requires total number of shop-tasks and sum of their stimulus.

Algorithm 4.1: Self-regulated task-allocation based on AFM

```

1: Input: AllTaskInfo, RobotPose, TaskRecords, DeltaDistance
2: Output: SelectedTaskID
3: comment: Stage 1: Get each task's individual stimuli and sum all stimulus
4: TotalTasks  $\leftarrow$  Total number of tasks  $\in$  AllTaskInfo
5: TaskStimuliSum  $\leftarrow$  0
6: for all Task  $\in$  AllTaskInfo do
7:   TaskPose  $\leftarrow$  Task-position  $\in$  Task
8:   TaskUrgency  $\leftarrow$  Task-urgency  $\in$  Task
9:   TaskSensitization  $\leftarrow$  Task-sensitization  $\in$  Task
10:  DistanceToTask  $\leftarrow$  CalculateTaskDistance(RobotPose, TaskPose)
11:  TaskStimuli  $\leftarrow$  CalculateTaskStimuli(DistanceToTask,
```

```

12:           TaskSensitization, TaskUrgency, DeltaDistance)
13:   TaskStimuliSum  $\leftarrow$  TaskStimuliSum + TaskStimuli
14:   TaskRecords  $\leftarrow$  UpdateTaskRecords(TaskStimuli,
15:           DistanceToTask, TaskUrgency, TaskSensitization)
16: end for
17: RandomWalkStimuli  $\leftarrow$  CalculateRandomWalkStimuli(TotalTasks,
18:           TaskStimuliSum)
19: AllStimuliSum  $\leftarrow$  TaskStimuliSum + RandomWalkStimuli
20: comment: Stage 2: Find probability of each task based on its stimuli
21: TaskID  $\leftarrow$  0
22: while TaskID  $\leq$  TotalTasks do
23:   TaskStimuli  $\leftarrow$  Task-stimuli  $\in$  TaskRecords(TaskID)
24:   TaskProbability  $\leftarrow$  GetTaskProbability(TaskStimuli, AllStimuliSum)
25:   TaskProbabilityRange  $\leftarrow$  ConvertTaskProbabilityIntoRange(
26:           TaskProbability)
27:   TaskRecords  $\leftarrow$  UpdateTaskRecords(TaskProbability)
28: end while
29: comment: Stage 3: Draw a random-number to match with TaskID
30: RandomNum  $\leftarrow$  GetRandomNumber(0, Max(TaskProbabilityRange))
31: while TaskID  $\leq$  TotalTasks do
32:   RangeStart  $\leftarrow$  Min(TaskProbabilityRange(TaskID))
33:   RangeEnd  $\leftarrow$  Max(TaskProbabilityRange(TaskID))
34:   if RandomNum  $\geq$  RangeStart && RandomNum  $\leq$  RangeEnd then
35:     SelectedTaskID  $\leftarrow$  TaskID
36:   end if
37: end while

```

Stage 2. In the second stage of this task-allocation algorithm, the probability of each task (including random-walk) can be found based on Eq. 5.7. Then this probability value of each task, between 0 and 1, is rounded to the closest two-digit fractions and multiplied by 100 and put into a linear scale. For example, if two tasks probability values are: 0.15 and 0.25, the probability range of first task becomes 0 to 15 and for second task, it becomes 16 to 40.

Stage 3. After converting each task's probability values into a linear range, a random-number generator is used that draws a random-number between 0 and the highest value of task-probability range, say 40 for the previous example. Then this random number is compared against the task probability range of each task. For the above example, if the random-number becomes 37, the task-probability range checking function selects *Task2* since 37 falls between 16 to 40. Under this probabilistic method, the task with larger probability range has a higher chance to be selected, but low probability tasks are also selected from time-to-time.

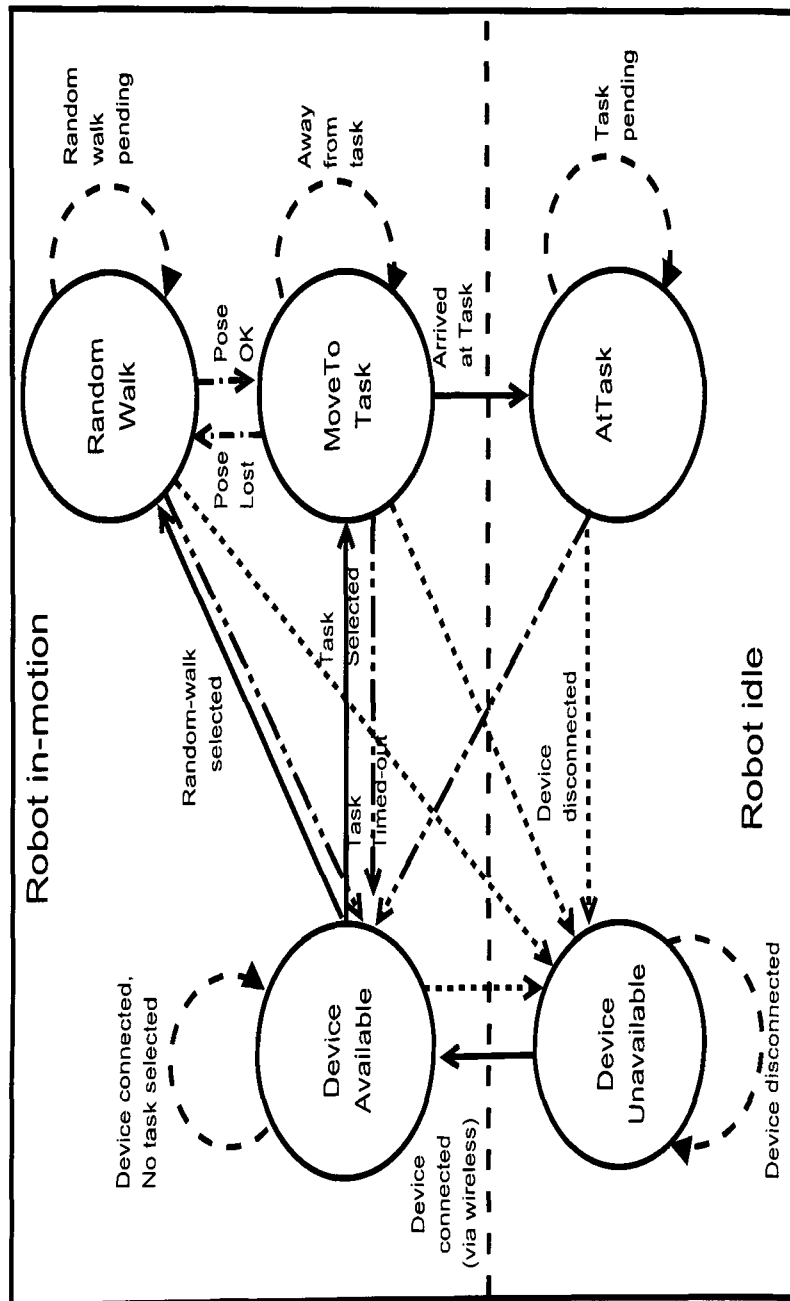


Figure 5.6: State diagram of DeviceController module

Algorithm 4.2: Robot's learning and forgetting of tasks based on AFM

```

1: Input: TaskRecords, LearnRate, ForgetRate, SelectedTaskID
2: Output: Updated TaskSensitization  $\in$  TaskRecords
3: for all Task  $\in$  TaskRecords do
4:   TaskID  $\leftarrow$  ID  $\in$  Task
5:   TaskSensitization  $\leftarrow$  Sensitisation  $\in$  Task
6:   if TaskID  $\equiv$  SelectedTaskID then
7:     TaskSensitization  $\leftarrow$  Max(1, (TaskSensitization + LearnRate))
8:   else
9:     TaskSensitization  $\leftarrow$  Min(0, (TaskSensitization - ForgetRate))
10:  end if
11: end for

```

Robot learning and forgetting algorithm:

Algorithm 4.2 lists the pseudo-code for updating the robot's task-sensitization values. Along with previously mentioned *TaskRecords*, and *SelectedTaskID*, it takes two other inputs: *LearnRate* (Δk_{INC}) and *ForgetRate* (Δk_{INC}) as outlined in Eq. 5.3 and 5.4 respectively. In addition to that it also keeps the value of task-sensitization between the fixed limit of 0 and 1.

DeviceController:

The final code that moves a robot to desired task location or make random-walk resides in DeviceController module. This is also a separate sub-process of Python Multiprocessing based mother process. It waits for the DataManager's mRobotPoseAvailable and mSelectedTaskAvailable events. When TaskSelector sets mSelectedTaskAvailable event, DeviceController sub-process checks the Bluetooth link-connectivity with physical robot. In case of successful task start-up it sets mSelectedTaskStarted event that, in turn, triggers SignalEmitter to emit a D-Bus signal publishing the robot's currently engaged task. The full state switching policies of

DeviceController is illustrated in Fig. 5.6. Externally one can observe two distinct physical state of a robot: it is either idle or in motion (separated by dotted line). These two physical states are mapped into several logical steps:

DeviceUnavailable: Initially, DeviceController sets its state as *DeviceUnavailable* (e.g. not connected with Bluetooth link) and after a fixed short-time

interval it checks whether the device has connected to host-PC, i.e. after the wireless link becomes up. In that case, `DeviceController` switches its state to *DeviceAvailable* (i.e. device connected). One can see that from every other state, device can come to this unavailable state (shown by dotted arrow) when the link is lost e.g. in case of robot's low battery or any other disconnection event (i.e. device disconnected).

DeviceAvailable: `DeviceController` stays in this state until `Data-Manager's mSelectedTaskAvailable` event fires (*Device connected, no task selected*). Then it switches to either *MoveToTask* or *RandomWalk* state depending on the selected task. `DeviceController` returns to this state from *RandomWalk*, *MoveToTask* or *AtTask* states after a pre-set task time-out period has elapsed. In that case it triggers the `DataManager's mTaskTimedOut` event.

RandomWalk: Robot can random walk in two cases: 1) when `TaskSelector` selects this random-walk task or 2) when the robot cannot get its pose information for a moment. The latter helps the pose tracker to recover the robot-pose from a crowd of robots. Robot continues to do random-walk until its task time-out period elapses or its pose remains unavailable from the pose tracker (i.e. random-walk pending).

MoveToTask: In this state, robot takes step-by-step navigation approach to reach a task boundary. Until the robot reaches the task boundary (*Away from task*), in every navigation-step it adjusts its heading to task based on both robot and task pose information and then makes a fixed-time translation movement. In worse cases, when time-out happens early before reaching a task `DeviceController` switches from this state to *DeviceAvailable* state. However, if the same task is selected immediately, it is more likely that it will go to *AtTask* state in next step.

AtTask: In this state `DeviceController` discovers itself near the task and normally until task time-out happens (i.e. task pending) it stays at this state.

5.5.3 Task-perception server

Similar to RCC, TPS has two D-Bus communication components `SignalListener` and `SignalEmitter`, and a data and event management component `DataManager` (Fig. 4.8).

Algorithm 4.3: Task-urgency update rules based on AFM

```

1: Input: AllTaskInfo, AllTaskWorkers, ThresholdWorkers,
2:       DeltaUrgencyINC, DeltaUrgencyDEC
3: Output: Updated TaskUrgencies  $\in$  AllTaskInfo
4: for all (Task, Workers)  $\in$  (AllTaskInfo, AllTaskWorkers) do
5:   TaskUrgency  $\leftarrow$  Task-urgency  $\in$  Task
6:   TaskWorkers  $\leftarrow$  Number of workers  $\in$  Workers
7:   if TaskWorkers  $<$  ThresholdWorkers then
8:     TaskUrgency  $\leftarrow$  Max(1, (TaskUrgency + DeltaUrgencyINC))
9:   else
10:    TaskUrgency  $\leftarrow$  Min(0, (TaskUrgency -
11:                               TaskWorkers  $\times$  DeltaUrgencyDEC))
12:   end if
13: end for

```

This instance of *DataManager* stores statistics about task performance of robots in a *dictionary* type data structure (*mTaskWorkers*). This data structure is updated every time a *RobotStatus* signal is received from a RCC. It is a dictionary type data structure where ID of tasks are keys and ID of robots are the values of this dictionary. Based on this data structure, an application layer component, *TaskInfoUpdater*, updates the task-urgencies after every short time intervals. This update algorithm is presented in Algorithm 4.3. Along with the static task-pose information, all task-urgencies are stored in the *mTaskInfo* data structure of *DataManager* of TPS. This TPS's *SignalEmitter* waits for the update of *mTaskInfo* and after every certain interval it emits this up-to-date *TaskInfo* signal.

This algorithm acts upon the task-urgency data of each task and updates it based on the active number of robots currently working on that task (Eq. 5.1 and 5.2). Here *AllTaskInfo* and *AllTaskWorkers* correspond to *mTaskInfo* and *mTaskWorkers* of TPS *DataManager* respectively. *ThresholdWorkers* are the minimum number of robots required to work on this task (μ). *DeltaTaskUrgencyINC* and *DeltaTaskUrgencyDEC* are the task-urgency increase and decrease rate which correspond to the small increase and decrease of work-load in every-step. This algorithm also keeps the values of task-urgencies within 0 and 1 limit by using generic *Min()* and *Max()* functions. Source-code of a Python implementation of TPS is

publicly accessible through GitHub repository³.

5.6 Results

In this section experimental results have been presented. Those experiments were up and running for about 40 minutes and average was taken from five iterations for both Series A and B.

Shop-floor work-load history

In these experiments, shop-floor work-load is defined in terms of task urgencies. For example, Eq. 5.8 shows how initial production work-load of the manufacturing shop-floor scenario can be calculated.

³[git://github.com/roboshepherd/CentralizedTaskServer.git](https://github.com/roboshepherd/CentralizedTaskServer.git), *hash*: 09187e28292d1cdc179c

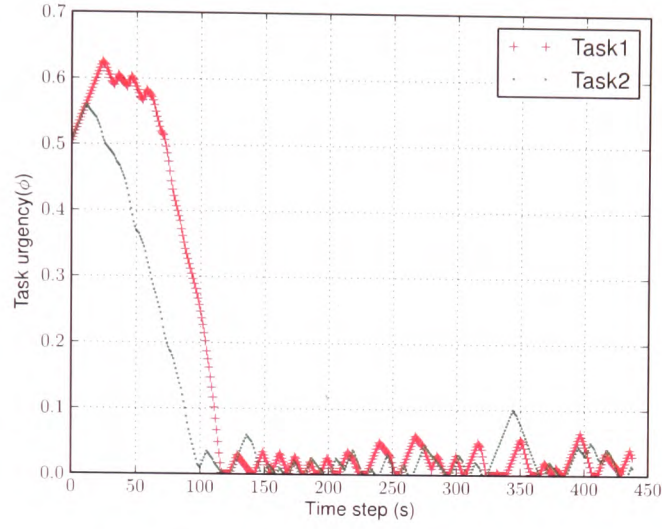


Figure 5.7: Changes in task-urgencies in Series A experiments

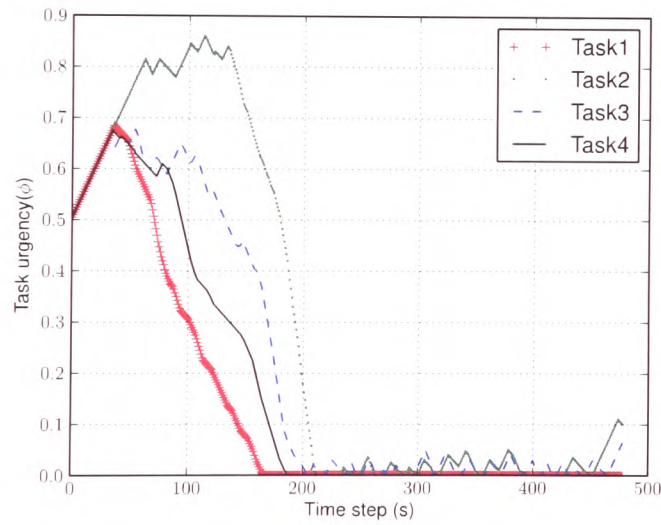


Figure 5.8: Changes in task-urgencies in Series B experiments

Fig. 5.7 and Fig. 5.8 show the dynamic changes in task-urgencies for the single iteration of Series A and Series B experiments respectively. The fluctuations in these plots have resulted from the different levels of task-performance of e-puck robots.

In order to measure the task-related work-loads on the system the changes in all task-urgencies are summed up over time. This is called as *shop-floor work-load history* and formalized as follows. Let $\phi_{j,q}$ be the urgency of a task j at q^{th} step and $\phi_{j,q+1}$ be the task urgency of $(q + 1)^{th}$ step. The sum of changes in urgencies of all M tasks can be calculated at $(q + 1)^{th}$ step:

$$\Delta\Phi_{j,q+1} = \sum_{j=1}^M (\phi_{j,q+1} - \phi_{j,q}) \quad (5.19)$$

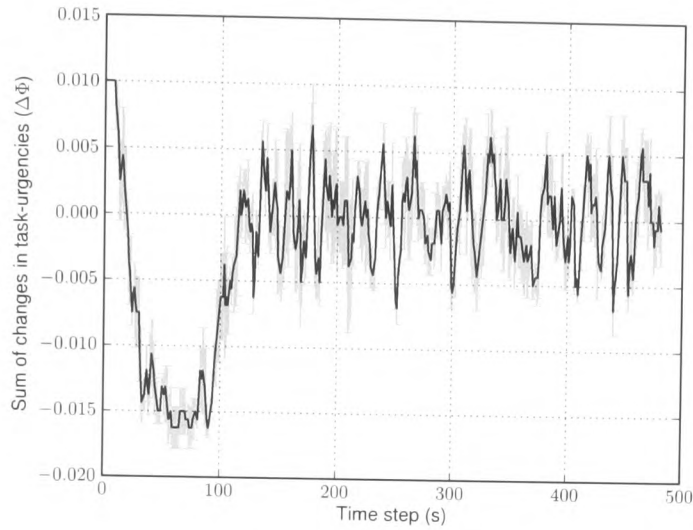


Figure 5.9: Shop-floor workload change history in Series A

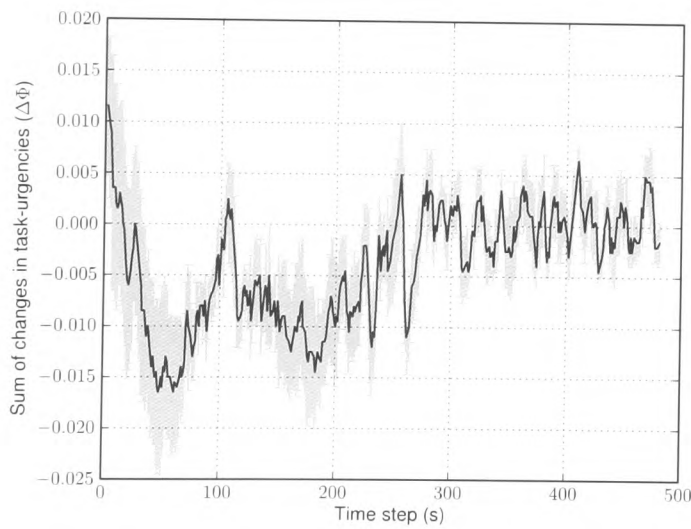


Figure 5.10: Shop-floor workload change history in Series B

Fig. 5.9 and Fig. 5.10 show the dynamic shop-floor workload for Series A and Series B experiments respectively. From these plots, it can be seen that initially the sum of changes of task urgencies (shop-floor workload) is going towards negative direction. This implies that tasks are being served by a high number of robots.

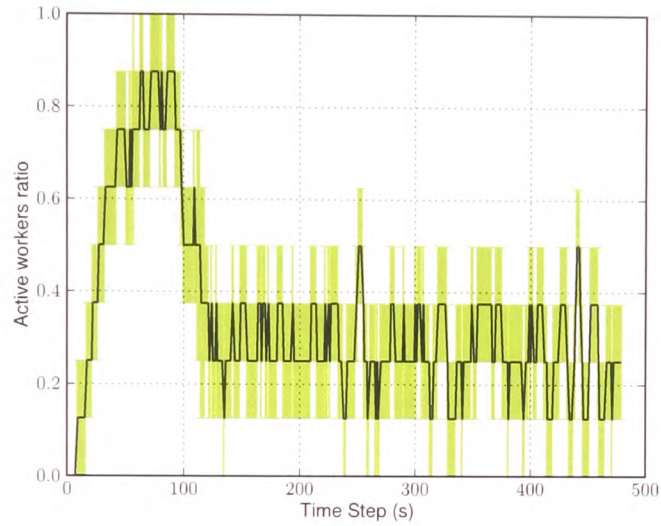
Ratio of active workers

Figure 5.11: Self-organized allocation of robots in Series A

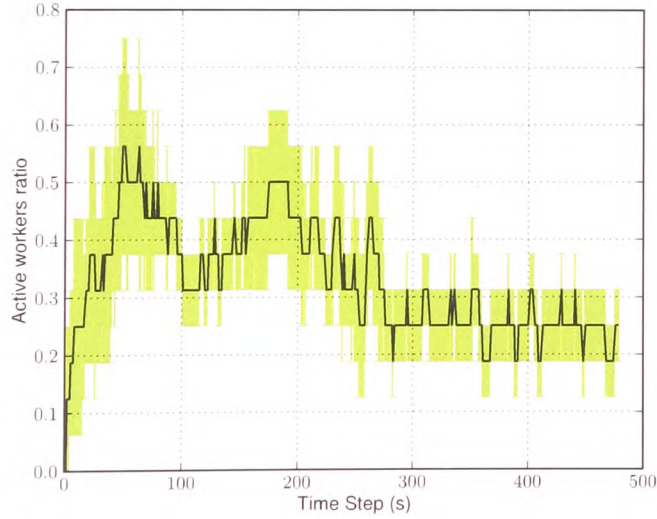


Figure 5.12: Self-organized allocation of robots in Series B

From both Fig. 5.11 and Fig. 5.12, one can see that in production stage, when work-load is high, many robots are active in tasks. Here active workers ratio is

the ratio of those robots that work on tasks to the total number of robots N of a particular experiment. Here one can see that this ratio varies according to the shop-floor work-load changes.

Shop-task performance

In the manufacturing shop-floor scenario, the APCD and APMW for both Series A and Series B experiments have been calculated. For Series A, the average production completion time is found at 111 time-step (555s) where sample size is $(5 \times 2) = 10$ tasks, $SD = 10$ time-steps (50s). According to Eq. 5.12, the theoretical minimum production completion time is 50 time-steps (250s) assuming the non-stop task performance of all 8 robots with an initial task urgency of 0.5 for all 2 tasks and task urgency decrease rate $\Delta\Phi_{DEC} = 0.0025$ per robot per time-step. Hence, Eq. 5.13 gives APCD, $\zeta = 1.22$ which means that in Series A experiments, it took 1.22 times more time (305s) than the estimated minimum production completion time (250s). For Series B, average production completion time is 165 time-steps (825s) where sample size is $(5 \times 4) = 20$ tasks, $SD = 72$ time-steps (360s). Hence, Eq. 5.13 gives APCD, $\zeta = 2.3$.

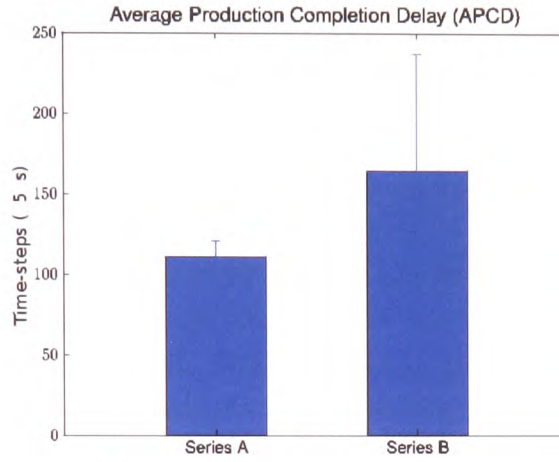


Figure 5.13: APCD of Series A and Series B experiments.

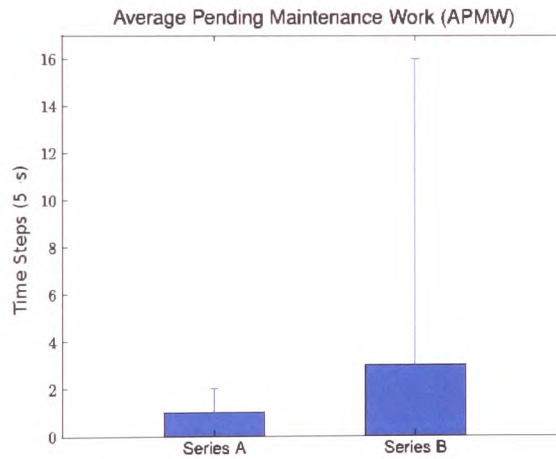


Figure 5.14: APMW of Series A and Series B experiments.

Fig. 5.13 shows the APCD for both Series A and Series B experiments. For APMW, Series A experiments give an average time length of 369 time-steps (1845s). In this period APMW is calculated and it corresponds to 1 time-step with $SD = 1$ time-step (5s) and $\Delta\Phi_{INC} = 0.005$ per task per time-step. This shows a very low APMW ($\chi = 0.000235$) and a very high robustness of the system. For Series B experiments, from the average 315 time-steps (1575s) maintenance activity of robots per experiment run, APMW has become $\chi = 0.012756$ which corresponds

to the pending work of 3 time-steps (15s) where $SD = 13$ time-steps (65s). This tells the robust task performance of e-puck robots which can return to an abandoned task within a minute or so. Fig. 5.14 plots the APMW for both Series A and Series B experiments.

Task specializations

The task-specialization of the robots have been measured based-on their peak value of sensitization. This maximum value represents how long a robot has repeatedly been selecting a particular task. Since tasks are homogeneous the maximum sensitization value of a robot among all tasks is considered during an entire experiment run. This value is then averaged for all robots using the following equation.

$$K_{avg}^G = \frac{1}{N} \sum_{i=1}^N \max_{j=1}^M (k_{j,q}^i) \quad (5.20)$$

If a robot r_i has the peak sensitization value k_j^i on task j ($j \in M$ tasks) at q^{th} time-step, Eq. 5.20 calculates the average of the peak task-specialization values of all robots for a certain iteration of the experiments. The time-step values (q) have been averaged to reach those peak values for all robots using the following equation.

$$Q_{avg}^G = \frac{1}{N} \sum_{i=1}^N q_{k=k_{max}}^i \quad (5.21)$$

In Eq. 5.21, $q_{k=k_{max}}^i$ represents the time-step of robot r_i where its sensitization value k reaches the peak k_{max} as discussed above. By averaging this peak time-step values of all robots one can have an overall idea of how many task-execution cycles are spent to reach the maximum task-specialization value K_{avg}^G .

Table 5.3: Peak task-sensitization values of robots in a Series A experiment.

Robot ID	Maximum k	At time-step (q)	Task
1	0.54	64	Task1
4	0.32	14	„
5	0.27	11	„
3	0.47	63	Task2
2	0.46	64	„
6	0.20	10	„
7	0.18	4	„
8	0.15	3	„

Table 5.4: Peak task-sensitization values of robots in a Series B experiment.

Robot ID	Maximum k	At time-step (q)	Task
24	0.41	29	Task1
13	0.31	19	„
16	0.18	4	„
1	0.64	66	Task2
35	0.34	12	„
5	0.28	14	„
22	0.18	20	„
17	0.16	6	„
3	0.14	12	„
9	0.68	66	Task3
6	0.43	71	„
15	0.19	4	„
14	0.15	4	„
31	0.14	4	„
19	0.22	12	Task4
12	0.16	10	„

Table 5.3 and Table 5.4 show sample peak sensitization values of Series A and Series B experiments respectively. Based on Eq. 5.20 and Eq. 5.21, the peak task-sensitization K_{avg}^G values are found as 0.40 (SD=0.08) and 0.30 (SD=0.03), and their respective time-step Q_{avg}^G values: 38 (SD=13) and 18 (SD=5) time-step.

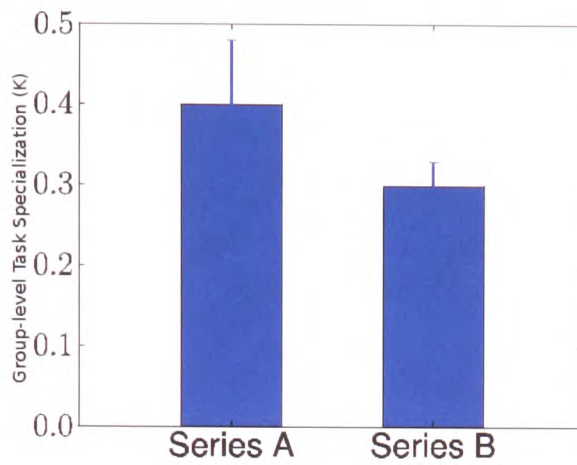


Figure 5.15: Overall task-specialization of robot groups.

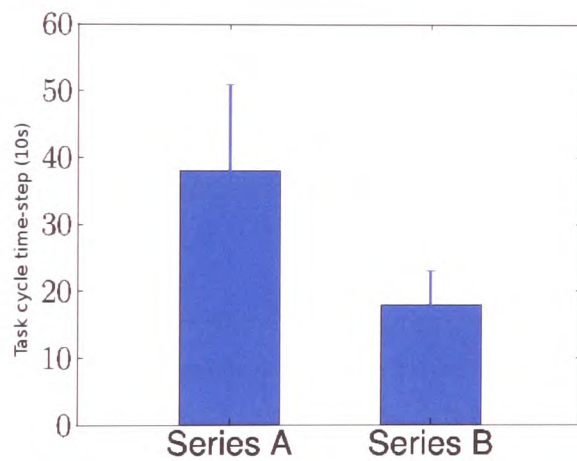


Figure 5.16: Time-steps to reach the peak values of task-specialization

They are shown in Fig. 5.15 and Fig. 5.16. Here one can see that the robots in Series A have higher chances of task-specialization than that of Series B experiments.

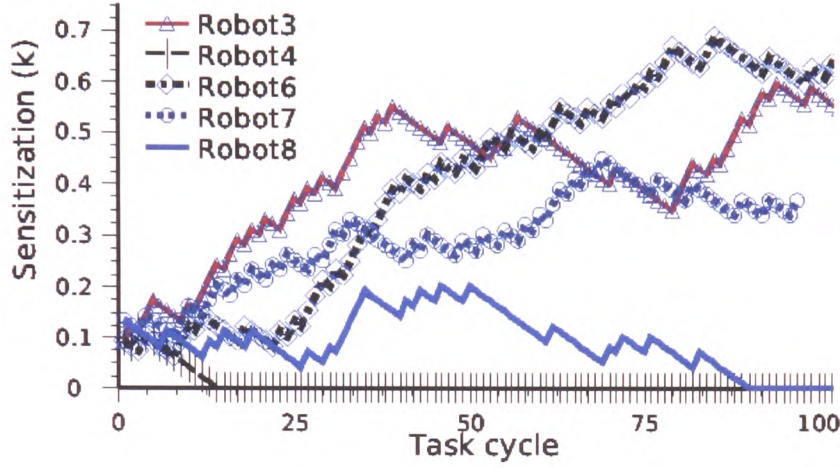


Figure 5.17: Task specialization on Task3 for a Series B experiment.

Fig. 5.17 shows the task specialization of five robots on Task3 in a particular run of Series B experiment. This shows how some of the robots can specialize (learn) and de-specialize (forget) tasks over time.

Robot motions

The changes in translation motion of all robots have been aggregated over time. Let $u_{i,q}$ and $u_{i,q+1}$ be the translations of a robot i in two consecutive steps. If the difference between these two translations be δu_i , one can find the sum of changes of translations of all robots in $(q+1)^{th}$ step using the following equation.

$$\Delta U_{q+1} = \sum_{i=1}^N \delta u_{i,q+1} \quad (5.22)$$

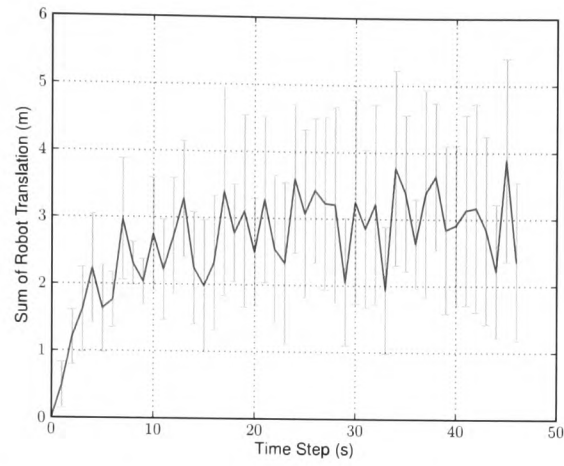


Figure 5.18: Sum of the translations of robots in Series A experiments

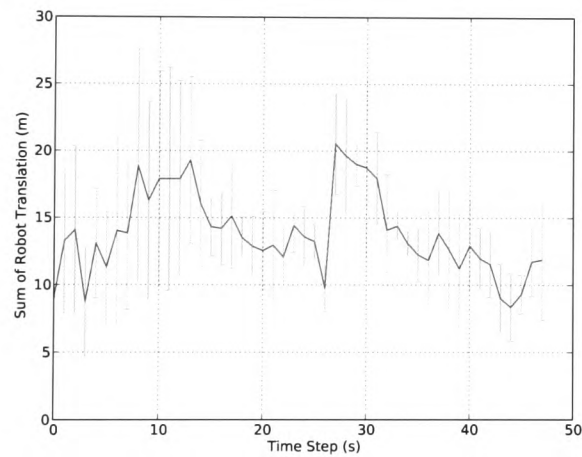


Figure 5.19: Sum of the translations of robots in Series B experiments

The results from Series A and Series B experiments are plotted in Fig. 5.18 and Fig. 5.19. In this plot one can see that robot translations also vary over varying task requirements of tasks.

Communication load

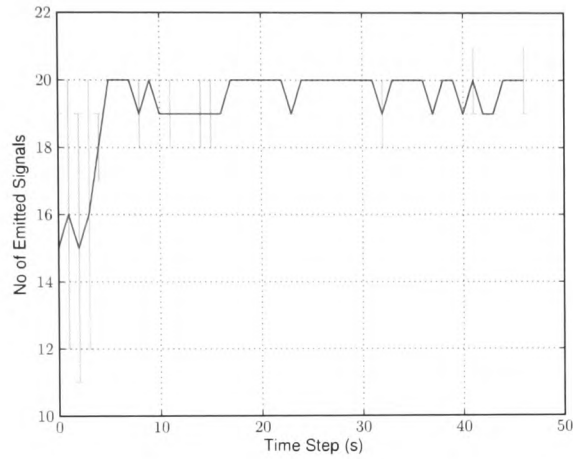


Figure 5.20: Frequency of TaskInfo signalling in Series A experiments

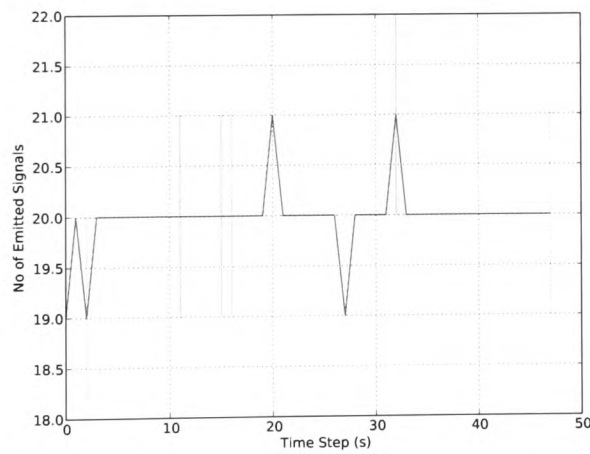


Figure 5.21: Frequency of TaskInfo signalling in Series B experiments

Fig. 5.20 and Fig. 5.21 show the number of received TaskInfo signals by each robot in Series A and Series B experiments. Since the duration of each time-step is 50s long and TPS emits signal in every 2.5s, there is an average of 20 signals in each time-step.

5.7 Discussions

Self-regulated DOL. From the experimental results, several aspects of self regulated DOL have been noted that exposes the power of AFM. As it is pointed out that this self-regulated DOL, as observed in biological and human social systems, needs to satisfy several important characteristics, e.g. plasticity, task-specialization. In addition to satisfying those basic qualities, AFM has demonstrated many other aspects. These self-regulated e-puck robots, driven by AFM, effectively handle the dynamic work-load of a manufacturing shop-floor. They can dynamically support the need to work on currently demanding tasks, if there are any. The variations of active worker ratio supports this.

From the self-organized worker allocations of AFM, it is clear that although in larger system (Series B) the degree of variations of active-worker ratio can show significantly unpredictable patterns, nevertheless the self-regulated rules drive the robots to respond to the dynamic needs of the system. This means that AFM can sufficiently produce the plasticity of DOL in order to meet the dynamic work-load of the system.

Learning and Forgetting. From the individual and group-level task specialization, one can see that robots can maintain both task-specialization and flexibility. In a self-organized system, it is very common that only a few individuals specialize on tasks and others generally do not. From two samples data sets, one can see that in particular runs of Series A and Series B experiments, task-sensitization values of only 2-3 robots reach above the group-level average score. Thus in both types of experiments, robots exhibit similar task-specialization behaviours.

From task-sensitization one can also see that a limited number of robots are specialized in tasks. Thus most of the other robots are flexible in selecting any tasks as their task-specializations do not bind them to particular tasks.

Concurrency and robustness. As a consequence of fewer robots specializing in tasks, one can also see that robots can concurrently consider different tasks without being biased to a particular task all the time. These experiments also show the robust DOL as in case of both high and low work-loads present in the system. This is evident from the manufacturing shop-floor task performance during PMM and MOM. For example, in case of Series B experiments APMW was 13 time-steps

(65s) which corresponded to pending work-load of 0.065 unit for a single robot. Thus, on average, before the work-load exceeded by about 13 percent of initial work-load, robots were able to respond to a task.

Communication load. In these experiments a centralized communication system (source of attractive fields) is used that serves the robots with necessary task-perception information. Although the robot-controllers software RCC was also co-located in the same host-PC, they can be distributed to several PCs or robot's on-board PCs. The centralized communication system has the advantage of minimising the communication load and the disadvantage of a single point of failure as well as a single point of load. In the next chapter the decentralized task perception is presented which uses P2P communications among RCCs.

Scaling-up. The system size of Series B is double than that of Series A in terms of robots, tasks and experiment arena. A fixed ratio of robot-to-task and task-to-arena has been kept in order to see the scaling effects in different experiments. Here both systems have shown sufficient self-regulated DOL, but task-performance in both systems has varied significantly. For example, the value of APCD in Series B is higher by 1.08. This means that performance is decreased in Series B experiments despite having the resources in same proportion in both systems. This occurs partly due to the greater stochastic effects found in task-allocation in a larger system, e.g. presence of more tasks produce higher stochastic behaviours in robot's task selection.

Similarly it is seen that in a larger system robots have less chances to specialize on tasks, as the Series B experiments show that the overall average task-specialization of the group K_{avg}^G is lower by 0.10 and it lasts for significantly less time (the difference of Q_{avg}^G of both systems is 20 time-steps). Thus, in a large group, robots are more likely to switch among tasks more frequently and this produces more translation motions which cost more energy (e.g. battery power) in task-performance.

Selection of limited number of trials/experiments. The justification for choosing five trials of experiments goes as follows. Real-robotic experiments face the actual challenge of real-world implementation unlike software simulation. Thus, what cannot be discovered in hundreds of simulation runs, can naturally appear in a single or a few runs of a real-robotic experiments. Thus a set of five trials have

been chosen that represent a realistic target for a single-man implementation of a fairly large multi-robot system. This choice is made after an insightful literature survey on the existing real-robotic systems. This decision has been influenced by some recent studies on swarm robotic systems, such as Pugh and Martinoli (2009), Rutishauser et al. (2009) and Agassounon et al. (2004).

5.8 Summary

In this chapter, The effectiveness of an inter-disciplinary generic model of self-regulated DOL, AFM, have been validated in order to address MRTA problem. AFM have been incorporated in a multi-robot system with 8 and 16 robots under a manufacturing shop-floor scenario. A centralized communication system has been instantiated to realize this model. Various aspects of this model have been evaluated, such as ability to meet dynamic task demands, individual task specializations, communication loads and flexibility in concurrent task completions. A set of metrics has been formalized to observe the self-regulated DOL in this system. From the experimental results, it is confirmed that AFM can meet the requirements of dynamic MRTA by the virtue of its self-regulatory principles.



Local Communication for Self-regulated MRTA

As outlined in Sec. 1.2, inspired by the LSLC strategy found in a kind of social wasps, *polybia*, a second set of MRTA experiments have been carried out. In this chapter, a local P2P communication model (LPCM) has been discussed based-on biological local communication strategies. In order to fit LPCM into the previous implementation of multi-robot system, as explained in Chapter 5, certain functionalities have been added. In this chapter, those additional features have been discussed. Finally, the results have been compared from both GSNC and LSLC based experiments in achieving self-regulated MRTA.

6.1 Motivations

From the understanding of different kinds of communication strategies of biological social systems (Sec. 2.2), it is obvious that an effective LSLC strategy can greatly enhance the self-regulated MRTA. In fact, most researchers in the field of swarm robotics now acknowledge that LSLC is one of the most critical components of a swarm robotic system, as global behaviours emerge from local interactions among the individuals and their environment. But how can one find a suitable LSLC scheme for robots?

In this study, the concepts of pheromone active-space of ants have been used to realize a simple LSLC scheme. As discussed in Sec. 2.2, ants use various

chemical pheromones with different active spaces (or communication ranges) to communicate different messages with their group members. Ants sitting near the source of this pheromone sense and respond quicker than others who wander in far distances. Thus both communication and sensing occurs within a small communication range¹. This concept of communication range or locality is used in LPCM.

In order to find a suitable range (or radius) of communication and sensing, many researchers proposed various models that is briefly discussed in Sec. 3.3.5. Some researchers have stated that this range can be set at design time based on the capabilities of robots. Some other researchers have argued that they can be dynamically varied over time depending on the cost of communication and sensing, e.g. density of peers, ambient noise in the communication channels, or even by aiming for maximizing information spread. In this study, the former approach has been followed as it is assumed that typically robots will not have the precise hardware to dynamically vary their communication and sensing ranges. The issue of selecting the best communication range has been left as a topic of future research.

6.2 A locality-based P2P communication model

6.2.1 General characteristics

LPCM relies on the local P2P communications among robots. Robots can communicate to their nearby peers within a certain communication radius, r_{comm} and they can sense tasks within another radius r_{task} . They exchange communication signals reliably without any significant loss of information. A robot R_1 is a *peer* of robot R_2 , if spatial distance between R_1 and R_2 is less than this r_{comm} . Similarly, when a robot comes within this r_{task} of a task, it can sense the status of this task. Although the communication and sensing range can be different based on robot capabilities, they are considered same for the simplicity of this implementation.

Local communication can also give robots similar task information as in centralized communication. In this case, it is not necessary for each robot to communicate with every other robot to get information on all tasks. Since robots can random

¹ Although, generally communication and sensing are two different issues, within the context of the self-regulated DOL, sensing have broadly been viewed as the part of communication process, either implicitly via environment, or explicitly via local peers.

walk and explore the environment it is assumed that for a reasonably high robot-to-space density, all tasks will be known to all robots after an initial exploration period. In order to update the urgency of a task, robots can estimate the number of robots working on a task in two ways: by either using their sensory perception (e.g., camera) or doing local P2P communication with others.

LPCM can be characterized in terms of three fundamental issues of communication (Gerkey and Mataric 2001).

1. Message content: *what to communicate?*
2. Communication frequency: *when to communicate?*
3. Target message recipients: *with whom to communicate?*

In a typical multi-robot system, message content can be categorized into two types: state of each individual robot and target task (goal) information (Balch 2005). The latter can also be subdivided into two types: 1) an individual robot's target task information and 2) information of all available tasks found in the system.

Regarding the first issue, this communication model is open. Robots can communicate with their peers with any kind of message. This model addresses the last two issues very specifically. Robots communicate only when they meet their peers within a certain communication radius (r_{comm}). Although in case of an environment where robots move relatively faster the peer relationships can also be changed dynamically. But this can be manipulated by setting the signal frequency and robot to space density to somewhat reasonably higher value.

In terms of target recipients, this model differs from a traditional publish/subscribe communication model by introducing the concept of dynamic subscription. In a traditional publish/subscribe communication model, subscription of messages happens prior to the actual message transmission. In that case prior knowledge about the subjects of a system is necessary. But in this model this is not necessary as long as all robots use a common addressing convention for naming their incoming signal channels. In this way, when a robot meets with another robot it can infer the address of this peer robot's channel name by using a shared rule. A robot is thus always listening to its own channel for receiving messages from its potential peers or message publishers. On the other side, upon recognizing a peer, a robot

sends a message to this particular peer. So here it is not necessary to create any custom subject name-space (Gerkey and Mataric 2001) and it does not require any hard-coding information in each robot controller about the knowledge of their potential peers *a priori*. Subscription is done automatically based on their respective r_{comm} .

6.2.2 Implementation algorithm

Algorithm 5.1: Locality based P2P Communication Model

```

1: Input:  $RobotID, r_{comm}, r_{task}, TaskInfoDB, RobotPose,$ 
2:    $ListeningBuffer, EmissionBuffer$ 
3: Output: updated  $TaskInfoDB$ 
4: comment: Perception of a task, if the robot is within  $r_{task}$ 
5:  $TaskPose \leftarrow$  Estimate/get pose of a task within  $r_{task}$ 
6:  $TaskUrgency \leftarrow$  Estimate/get urgency of a task within  $r_{task}$ 
7:  $TaskInfo \leftarrow (TaskPose, TaskUrgency)$ 
8:  $TaskInfoDB \leftarrow \text{UpdateTaskInfoDB}(TaskInfo)$ 
9: comment: Listening  $LocalTaskInfo$  signal(s) from peers
10:  $RobotPeers \leftarrow$  Identify/get a list of peers within  $r_{comm}$ 
11: for all  $peer \in RobotPeers$  do
12:   if (caught a  $LocalTaskInfo$  signal from nearby peer) then
13:      $ListeningBuffer \leftarrow LocalTaskInfo$  of peer
14:      $TaskInfoDB \leftarrow \text{UpdateTaskInfoDB}(ListeningBuffer)$ 
15:   end if
16: end for
17: comment: Emitting own  $LocalTaskInfo$  signal to peers
18:  $EmissionBuffer \leftarrow TaskInfoDB$ 
19: for all  $peer \in RobotPeers$  do
20:    $\text{EmitLocalTaskInfoSignal}(peer, EmissionBuffer)$ 
21: end for
22:  $RobotPeers \leftarrow 0$ 

```

Within the context of the self-regulated MRTA experiments under AFM, the following aspects of LPCM have been formalized into an implementation algorithm.

1. Local sensing of peers and tasks.
2. Listening to the task-information peer signals.
3. Emitting local task-information signals to peers.

From Algorithm 5.1, it is seen that a robot controller is initialized with its specific *RobotID* and default values of r_{comm} and r_{task} that correspond to the robot's communication and sensing range respectively. These values are same for all robots and for all tasks. Initially a robot has no information about tasks, i.e. *TaskInfoDB* is empty. It has neither received nor transmitted any information yet, i.e. corresponding data buffers, *ListeningBuffer* and *EmissionBuffer*, are also empty. Upon sensing a task, robot determines the task's pose and urgency of that task (according AFM rules described in Sec. 5.2.5). This is not strictly necessary as this information can also be available from alternate sources, e.g. via communicating with a TPS which is discussed later.

Robot controller then executes the **UpdateTaskInfoDB()** that modified the robot's information about the corresponding task. In second step, robot senses its nearby peers located within r_{comm} and add them in *RobotPeers*. The potential *LocalTaskInfo* signal reception from a peer again triggers the **UpdateTaskInfoDB()** function. In the last step, robot emits its own task information as a *LocalTaskInfo* signal to its peers. Finally it cleans up the current values of *RobotPeers* for running a new cycle.

6.3 Experiment design

Table 6.1: Experimental parameters of Series C & D experiments

Parameter	Series C	Series D
task-perception range (r_{task})	0.5m	1m
Communication range (r_{comm})	0.5m	1m
Total number of robots (N)	16	
Total number of tasks (M)	4	
Experiment area (A)	4 m ²	

The local communication experiments follow a similar design of experimental parameters and observables of Series B experiments as outlined in Sec. 5.4. Table 6.1 highlights major parameters of these experiments. Here, one can see that there are two new parameters in Series C and Series D experiments, i.e. communication and sensing ranges. For the sake of simplicity, both of these values are kept same in both series of experiments.

Series D uses larger communication range that enables robots to capture more task information at a time. That is similar to “global sensing and global communication” of information by the robots, since in a large group of robots, it is not practical that a robot communicates with all other robots. On the other hand, Series C uses the half of the range values of Series D. This enables e-puck robots to capture less information, that mimics a true LSLC strategy. The main motivation for using two different ranges is to find any significant difference in performance from these two types of experiments.

6.4 Implementation

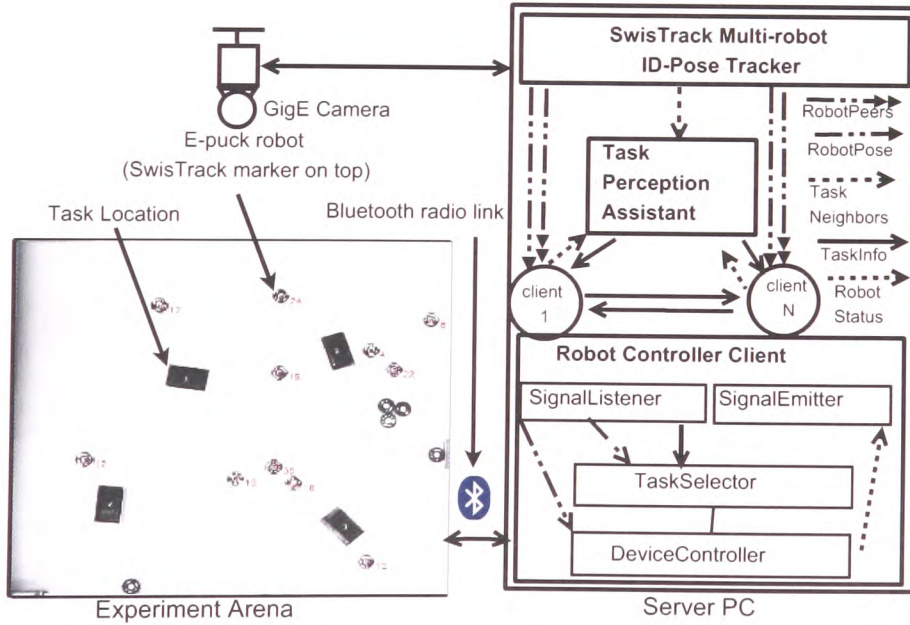


Figure 6.1: Hardware and software setup under local communication experiments.

As outlined in Fig. 6.1, on top of the base implementation of a multi-robot system, LPCM has been fitted into an extension of it. The additional communication interfaces and changes in RCC and TPS implementation are mentioned here. The details of the multi-robot system implementation can be found in Sec. 5.5.

Additional communication interfaces under LPCM

three new D-Bus signal interfaces have been added in this version of implementation. They are briefly discussed below.

RobotPeers: This signal is emitted by SwisTrack to each robot's signal path in a common `ac.uk.newport.ril.SwisTrack` interface. The payload of this signal contains the list of IDs of peers of each robot within its r_{comm} . These peer-IDs are extracted by analysing the captured image frame. This signal is caught by RCCs and used in emitting the `LocalTaskInfo` signal (discussed below).

TaskNeighborhood: This signal is emitted by SwisTrack for TPS and the payload of this signal contains the list of IDs of robots that are co-located within a task's perception range, r_{task} . TPS catches one signal per task and based-on the robot IDs, it emits the `TaskInfo` signal to those robot's RCC path (as discussed in Sec. 5.5).

LocalTaskInfo: This signal is emitted by RCCs to their peers that are co-located within the same communication range r_{comm} . The payload of this signal contains the known task information of a RCC. This task-information can be gathered either through task-perception (via `TaskInfo` signal received from TPS) or via communications i.e. through `LocalTaskInfo` signals from its peers.

Modifications in RCC and TPS

As shown in Fig. 6.1, RCCs disseminate task information to each other by `LocalTaskInfo` D-Bus signal. The contents of task information are physical locations of tasks and their urgencies. However as e-puck robots are incapable of sensing task directly. So it relies on TPS for a task-perception signal, `TaskInfo`, that contains the actual task location and urgency. When a robot r_i comes within r_{task} of a task j , SwisTrack reports it to TPS (by `TaskNeighbors` signal) and TPS then gives it current task information to r_i by `TaskInfo` signal. As discussed before, TPS catches feedback signals from robots via `RobotStatus` signal. This

can be used to inform TPS about a robot's current task id, its device status and so on. TPS uses this information to update relevant part of task information such as, task-urgency. This up-to-date information is encoded in next `TaskInfo` signal.

From the above discussions, one can see that the base implementation of RCC's task-allocation (i.e. `TaskSelector`) is almost unchanged in this local implementation. The only thing one needs to extend is the D-Bus signal reception and emission interfaces that catches the above signals and put the signal payload in `DataManager`. For the sake of simplicity, the perceived `TaskInfo` is merged with communicated `LocalTaskInfo` into one so that `TaskAllocator` always gets all available task information. No major change is made in other modules of RCC, i.e. `DeviceController`. The full Python implementation of this RCC is available for download from the GitHub repository².

In the base implementation TPS periodically broadcasts `TaskInfo` signals to all robots. But in this local version, TPS only emits `TaskInfo` signal when a robot is within a task's perception range, r_{task} based-on the `TaskNeighbour` signal from `SwisTrack`. For this additional interface, D-Bus `SignalListener` is extended to catch this additional D-Bus signal. No major changes are done in the other parts of TPS implementation. The full Python implementation of TPS is available for download from the GitHub repository³.

6.5 Results

Below the results from Series C and Series D experiments are organized by following the organization of results in Chapter 5.

²<http://github.com/roboshepherd/EpuckDistributedClient>

³<http://github.com/roboshepherd/DitributedTaskServer>

Shop-floor work-load history

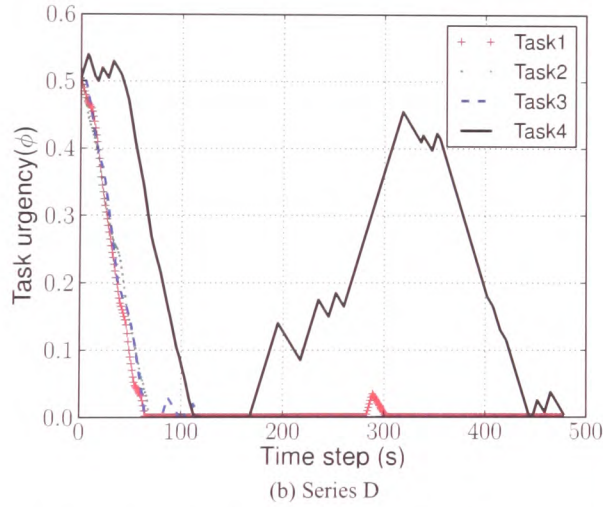
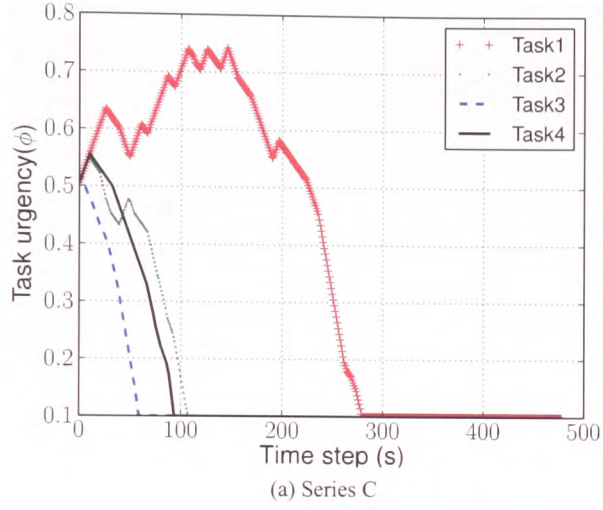
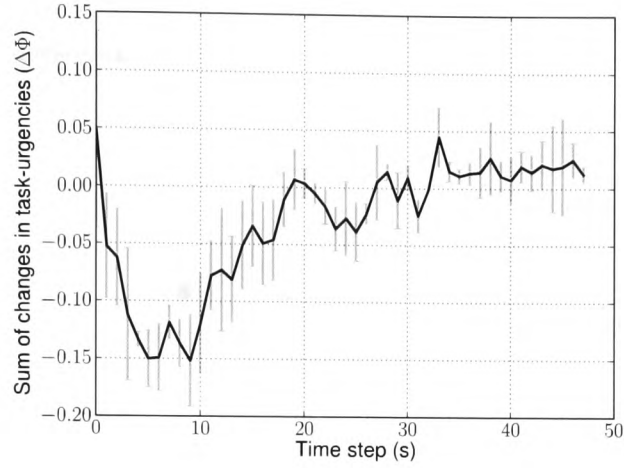
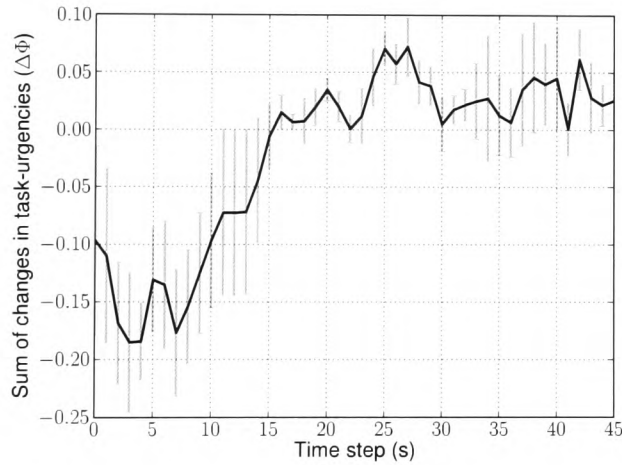


Figure 6.2: Task-urgencies observed in (a) Series C and (b) Series D experiments

The sample raw task-urgencies of Series C and Series D experiments are shown in Fig. 6.2. In case of Series D, one can see that an unattended task, *Task4*, was not served by any robot for a long period and later it was picked up by some of the robots.



(a) Series C



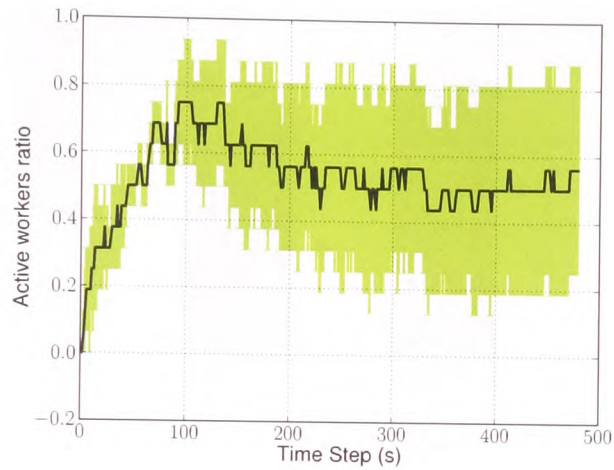
(b) Series D

Figure 6.3: Shop-floor work-load history (a) Series C and (b) Series D experiments

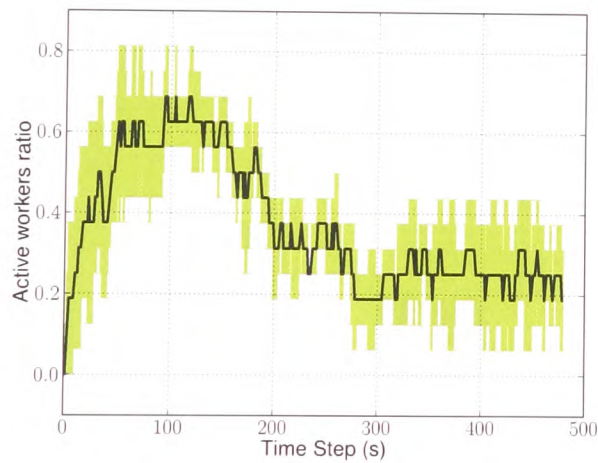
The dynamic shop floor work-load is shown in Fig. 6.3. These plots show similar work-load as experienced in Series A and Series B experiments. Here, one can also see that initially the sum of changes of task urgencies are towards negative direction. This implies that tasks are being served by a high number of robots. When the task urgencies stabilize near zero the fluctuations in urgencies become minimum. Since robots chose tasks stochastically, there will always be

small changes in task urgencies.

Ratio of active workers



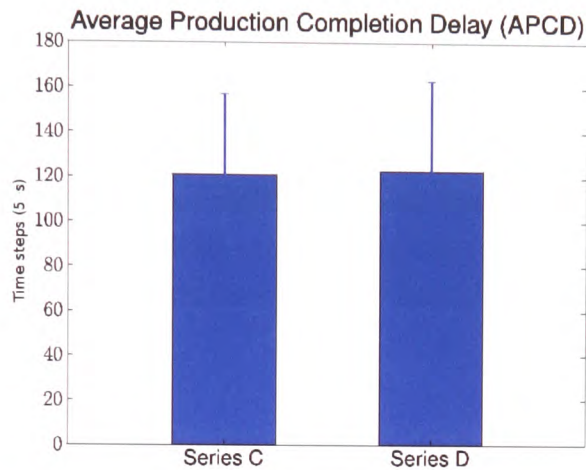
(a) Series C



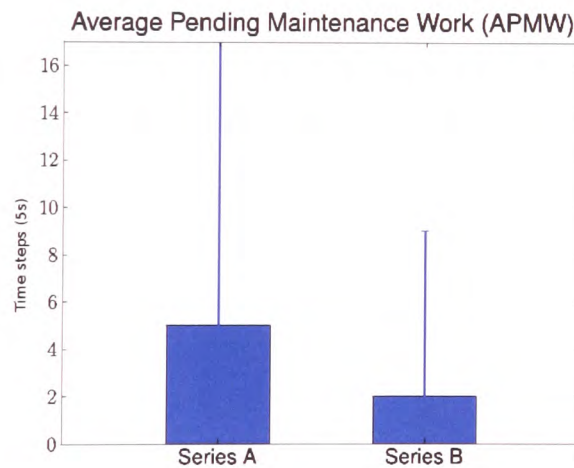
(b) Series D

Figure 6.4: Self-organized allocation of workers in (a) Series C and (b) Series D

The active worker ratios of both Series C and Series D experiments are plotted in Fig. 6.4. Series C data shows a large variation in this active worker ratios.

Shop-task performance

(a) APCD



(b) APMW

Figure 6.5: Task-performance of the shop-floor manufacturing scenario (a) APCD and (b) APMW

The task-performance of the manufacturing shop-floor scenario under both Series C and Series D experiments are plotted in Fig. 6.5. For Series C average production completion time is found as 121 time-steps (605s) with SD = 36 time-steps (180s). For Series D, average production completion time is 123 time-steps (615s) with SD

= 40 time-steps (200s). According to Eq. 5.12, the theoretical minimum production completion time is 50 time-steps (250s) as discussed in Sec 5.6. The values of APCD are as follows. For Series C, $\zeta = 1.42$ and for Series D, $\zeta = 1.46$. For both series of experiments APCD values are very close.

For APMW, Series C experiments give an average time length of 359 time-steps (1795s). In this period calculated APMW is 5 time-steps with SD = 17 time-steps and $\chi = 0.023420$. For Series D experiments, from the average 357 time-steps (1575s) of maintenance activity of e-puck robots per experiment run, APMW, χ is 0.005359 which corresponds to the pending work of 2 time-steps (10s) where SD = 7 time-steps.

Task specializations

Table 6.2: Peak task-sensitization values of robots in a Series C experiment.

Robot ID	Maximum k	At time-step (q)	Task
16	1.00	52	Task1
12	0.58	24	„
1	0.16	2	„
13	0.13	1	„
9	1.00	41	Task2
3	0.55	23	„
19	0.24	6	„
35	0.24	6	„
15	0.13	1	„
33	0.13	2	„
6	0.61	29	Task3
31	0.59	35	„
5	0.13	1	„
17	0.36	10	Task4
20	0.09	1	„
22	0.09	1	„

Table 6.2 and Table 6.3 show two sets of sample peak sensitization values of Series C and Series D experiments respectively. Based on Eq. 5.20 and Eq. 5.21, the peak task-sensitization K_{avg}^G values are 0.39 (SD=0.17) and 0.27 (SD=0.10), and their respective time-step Q_{avg}^G values: 13 (SD=7) and 11 (SD=5) time-step.

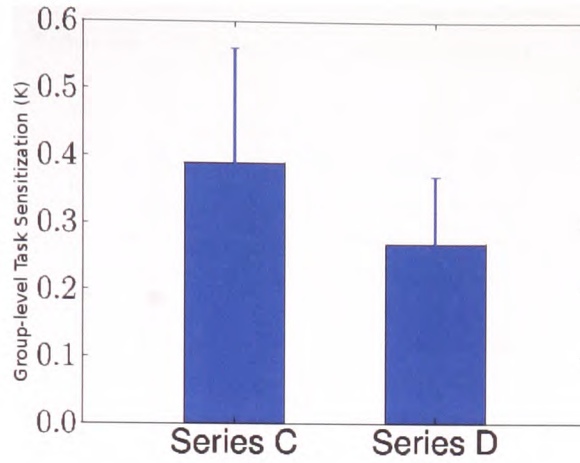


Figure 6.6: Overall task-specialization of robot groups.

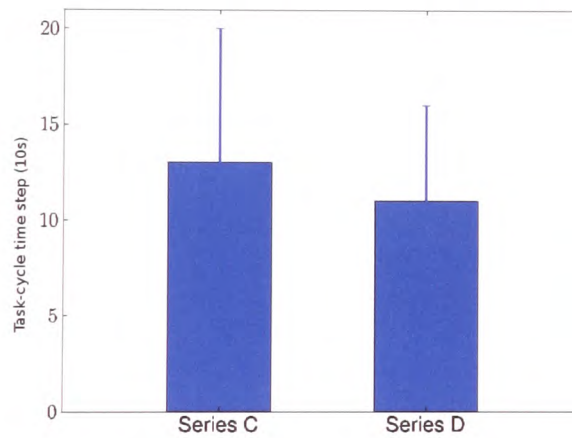


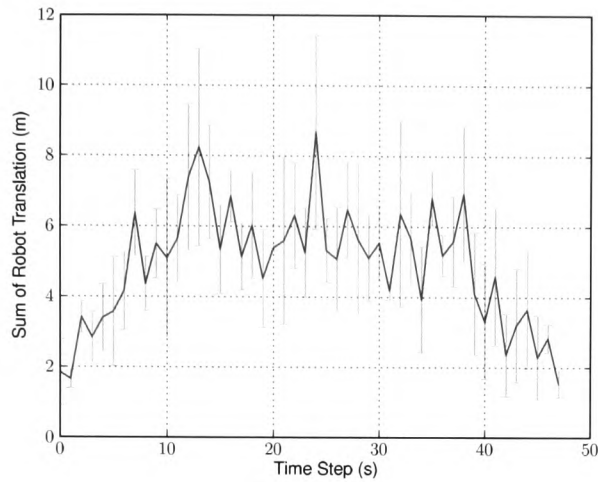
Figure 6.7: Time-steps to reach the peak values of task-specialization

They are shown in Fig. 6.6 and Fig. 6.7. Here one can see that the robots in Series C exhibited higher task-specialization than that of Series D experiments.

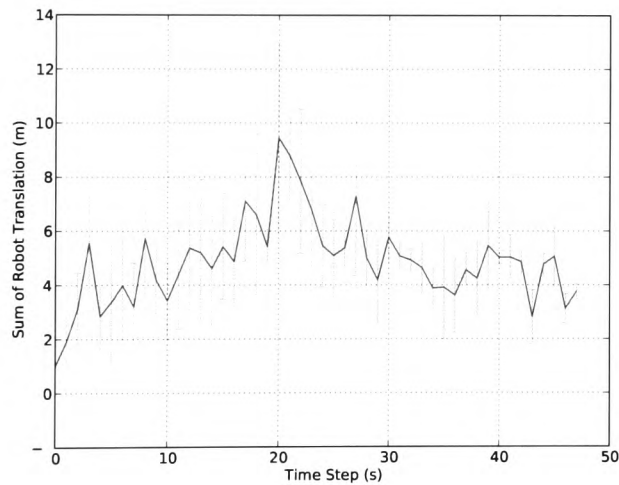
Table 6.3: Peak task-sensitization values of robots in a Series D experiment.

Robot ID	Maximum k	At time-step (q)	Task
19	1.00	34	Task1
35	1.00	60	„
24	0.41	16	„
12	0.20	6	„
1	1.00	41	Task2
31	1.00	47	„
22	0.40	10	„
9	0.38	12	„
15	0.16	2	„
33	0.13	1	„
5	0.92	70	Task3
13	0.74	36	„
17	0.76	62	Task4
6	0.22	4	„
3	0.13	2	„
16	0.13	1	„

Robot motions



(a) Series C

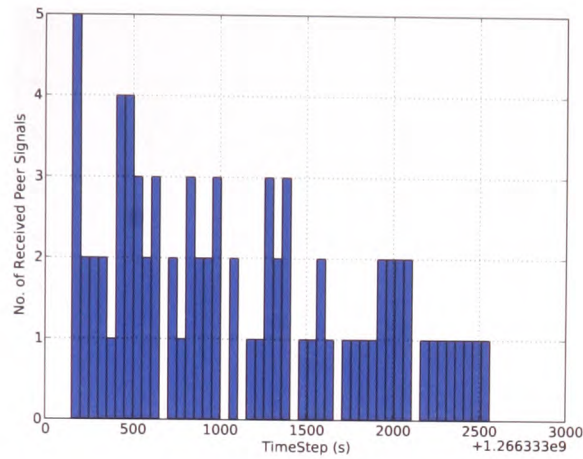


(b) Series D

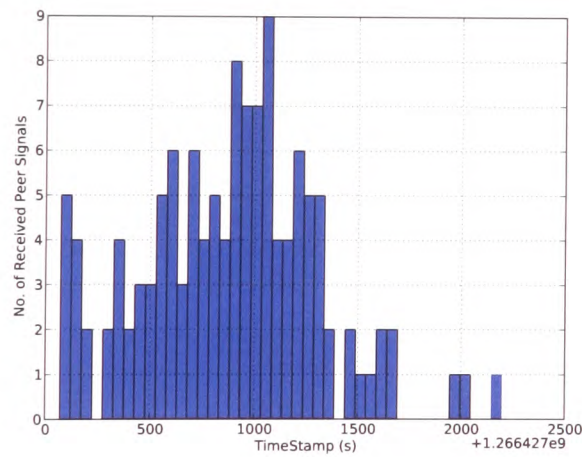
Figure 6.8: Sum of translations of all robots (a) Series C and Series D experiments

The changes in translation motion of all robots have been aggregated over time following Eq. 5.22. The robot translation results from both local mode experiments are plotted in Fig. 6.8. In this plot one can see that robot translations also vary over varying task requirements of tasks.

Communication load



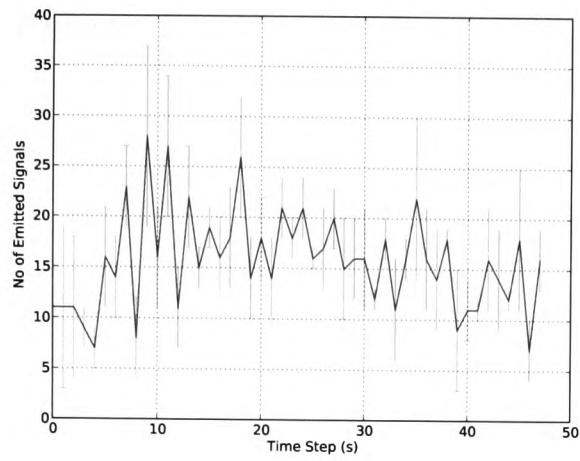
(a) Series C



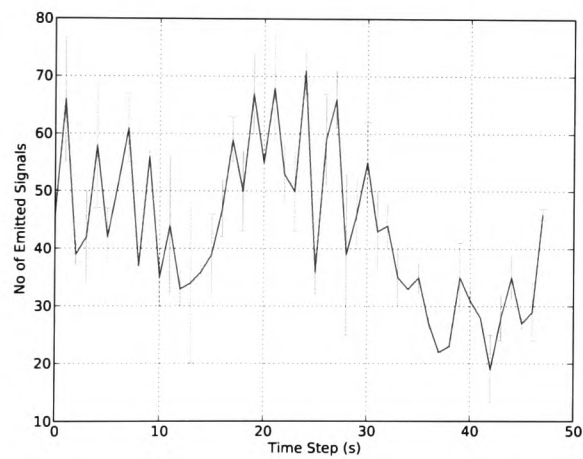
(b) Series D

Figure 6.9: LocalTaskInfo (P2P) signals caught by Robot12 in (a) Series C and (b) Series D experiment

As an example of P2P signal reception of a robot, Fig. 6.9 show the number of received signals by Robot12 in two local experiments. It states the relative difference of peers over time in two local cases.



(a) Series C



(b) Series D

Figure 6.10: Frequency of overall LocaltaskInfo (P2P) signalling in (a) Series C and (b) Series D experiments

The overall P2P task information signals of both of these local modes are plotted in Fig. 6.10.

6.6 Comparison of centralized and local communication experiments

Table 6.4: Shop-floor production and maintenance task performance

Experiment Series	<i>Production delay (SD) s</i>	<i>p-value</i> 1-tailed t-test (confidence)	<i>Pending maintenance time (SD) s</i>	<i>p-value</i> 1-tailed t-test
A	555 (50)	0.0	5 (5)	0.0
B	825 (360)	0.2 (60%)	15 (65)	0.0
C	605 (180)	N/A	25 (85)	N/A
D	615 (200)	0.0	10 (35)	0.0

Results from Series C and Series D experiments show many similarities and differences with respect to the results of Series A and Series B experiments. As shown in Table 6.4 both Series C and Series D experiments show similar production delay (APCD) values: 605s and 615s respectively, which are less than Series B experiment result (825s) and are close to Series A experiment result (555s). Note that all statistical t-test results are obtained with respect to Series C data and it shows that there is no significant difference in task-performance between Series B and Series C results.

Table 6.5: Task-specialization values of the robots

Experiment Series	K_{avg}^G (SD)	<i>p-value</i> 1-tailed t-test (con- fidence)	Q_{avg}^G (SD)	<i>p-value</i> 1-tailed t-test (confidence)
A	0.40 (0.08)	0.0	38 (13)	0.001 (99.8%)
B	0.30 (0.03)	0.2 (60%)	18 (5)	0.2 (60%)
C	0.39 (0.17)	N/A	13 (7)	N/A
D	0.27 (0.1)	0.0	11 (5)	0.0

Besides, in terms of task-specialization as shown in Table 6.5, the overall task-specialization of group in Series C ($K_{avg}^G = 0.4$) is closer to that of Series A experiments ($K_{avg}^G = 0.39$) and interestingly, the value of Series D ($K_{avg}^G = 0.27$) is much closer to that of Series B experiments ($K_{avg}^G = 0.30$). So task-specialization

in large group under LSLC strategy is not significantly different than their GSNC counter part.

Table 6.6: Sum of translations of robots in all experiments.

Experiment Series	Average translation (SD) m	<i>p-value</i> 1-tailed t-test (confidence)
A	2.631 (0.804)	N/A
B	13.882 (3.099)	0.001 (99.8%)
C	4.907 (1.678)	N/A
D	4.854 (1.592)	0.0

Table 6.6 summarizes the average translations done by robots in all four series of experiments. From these robot motion profiles, it is found that under LSLC strategy, robot translations have been reduced significantly. From this table it is seen that Series C and Series D show about 2.8 times less translation than that in Series B experiments. The translation of 16 robots in Series C and Series D experiments are approximately double (1.89 times) than that of Series A experiments with 8 robots. Thus the energy-efficiency under LSLC strategy seems to be higher than that under GSNC strategy.

From the above results one can see that large group robots achieve similar or better MRTA under LSLC strategy. The local sensing of tasks prevents them to attend a far-reaching task which may be more common under global sensing strategy. However, as it is seen in Fig. 6.2 some tasks can be left unattended for a long period of time due to the failure to discover it by any robot. For that reason it is seen that the values of pending maintenance load is slightly higher under LSLC strategy. But this trade-off is worthy as LSLC strategy provides superior self-regulated MRTA in terms of task-performance, task-specialization and energy-efficiency.

6.7 Summary

In this chapter, a locality based dynamic P2P communication model has been presented that follows the LSLC strategy for achieving self-regulated MRTA. It is seen that this implementation of local strategy achieves similar or better self-regulated

MRTA than its centralized counterpart. Particularly, the reduction in robot movement states that the local model is preferable when one needs to minimize robot energy usage. This model assumes no prior knowledge of the environment and it also does not depend on the number of the robots. An abstract algorithm has been presented that can be used with various P2P communication technologies. The implementation of this algorithm is reported by using the multi-robot control architecture, HEAD.

Comparative results from the experiments shows that robots relatively perform similar or better under LSLC strategy when the radius of communication is relatively small. More information exchange with larger communication radius, or with GSNC strategy, reduces the degree of task-specialization of robots. By limiting the local information exchange, robots have more chances to select local tasks and specialize on them, by the virtue of their self-regulating principles. Thus under LSLC strategy with smaller information exchange range, robots exhibit energy-efficient self-regulated MRTA.

Conclusions

The benefits of deploying a large number of robots in dynamic multi-tasking environment can not fully be realized without adopting an effective communication and sensing strategy for a given multi-robot system. This study has focused on comparing two bio-inspired communication and sensing strategies in producing self-regulated MRTA by an interdisciplinary model of DOL, AFM. Under the GSNC strategy, AFM has produced the desired self-regulated MRTA among a group of 8 and 16 robots. This gives the evidence that AFM can successfully solve the MRTA issue of a complex multi-tasking environment like a manufacturing shop-floor. Under the LSLC strategy, AFM can also produce the desired self-regulated MRTA for 16 robots with different communication and sensing ranges.

From the comparative results, it can be concluded that for large group of robots, degradation in task-performance and task-specialization of robots are likely to occur under GSNC strategy that relies upon a centralized communication system. Thus GSNC strategy can give better performance when the number of tasks and robots are relatively small. This confirms the assertions made by some biologists that self-regulated DOL among small group of individuals can happen without any significant amount of local communications and interactions. However, these findings suggest that task-specialization can still be beneficial among the individuals of a small group which contradicts the claim that small groups only possess the generalist workers, but not the specialists.

On the other hand, LSLC strategy is more suitable for large group of individuals that are likely to be unable to perform global sensing and global communications with all individuals of the group. The design of communication and sensing range still remains as a critical research issue. However, these results suggest that the idea of maximizing information gain is not appropriate under a stochastic task-allocation process, as more information causes more task-switching behaviours that lowers the level of task-specialization of the group. This might not be the case under a deterministic task-allocation scheme where more information leads to better and optimum allocations, but that is limited to a small group of individuals. Nevertheless, despite having the limited communication and sensing range, LSLC strategy helps to produce comparatively better task-allocation with increased task-specialization and significantly reduced motions or savings in energy e.g. battery power.

This study has experienced all the major challenges of implementing a large multi-robot system within limited time and resource constraints. From these experiences it can be said that by following flexible and open-source hardware and software platforms, it is possible to construct a large multi-robot system for conducting real-robotic experiments within limited time-frame. This is good news for those who want to test their models using a large real-robotic system without relying on simulation only. However in this case, one needs to adopt an appropriate test-driven bottom-up development approach, instead of following the traditional top-down “model - simulate - export-to-real-robots” approach.

7.1 Contributions

The general contributions of this thesis are listed below.

- **Self-organization:** Here it is found that self-organized allocation may produce specialized workers even when the group size is *small* (< 10), unlike assuming generalist workers prevents specialization in small groups (Garnier et al. 2007).
- **Task-allocation:** This study relates the selection of appropriate communication strategy with effective task-allocation of a large group of individuals.

Here it is found that local communication in task-allocation may outperform centralized one in terms of energy usage.

- **System development:** This empirical study shows that bottom-up decoupled construction of a fairly large artificial system yields higher advantages, particularly flexibility and integration with inter-operable elements.

The specific contributions of this thesis are as follows:

- **Interpretation of AFM as a basic mechanism of self-regulated MRTA.** As discussed in Chapter 5, AFM can be interpreted in a multi-robot manufacturing shop-floor scenario. In this process the generic part of the model has been separated out, e.g. providing learning and forgetting rate, from the domain-specific part, e.g. defining task-urgency increase and decrease rate. Similar interpretations can also be made in other task-domains. This study can be used as a guide to any such future application of AFM.
- **Validation of AFM through experiments with reasonably large number of real robots i.e. 16 e-puck robots.** It can be very difficult to realize an abstract model without having a practical example implementation of it. Mere computer simulation of a model cannot be considered enough. In this thesis, a rich implementation of AFM has been provided with detail algorithms and links to source code. This implementation can be replicated in solving many real-world tasks and resource allocation problems, e.g. resource allocation in automation industries.
- **Comparisons of the performances of two bio-inspired communication and sensing strategies in achieving self-regulated MRTA.** Since AFM has wrapped the communication and sensing of agents in a system-wide continuous flow of information, one needs to instantiate an instance of communication system to provide an infrastructure for this information flow. In this study, two well-known bio-inspired communication and sensing strategies, GSNC and LSLC, have been tested and measured their impact on self-regulated MRTA of a fairly large group of robots. This comparison provides an overall understanding of information exchange strategies commonly found in various social systems.

- **Development of a flexible multi-robot control architecture using D-Bus IPC technology.** In this thesis, the foundation of a new kind of robot control architecture has been laid down that uses the state-of-the-art D-Bus IPC protocol for decoupling the communication among various software components of a large multi-robot system. This greatly helps to reduce the bottlenecks in developing many heterogeneous software components using different programming languages and software frameworks.
- **Classification of MRTA solutions based on three major axes: organization of task-allocation, communication, interaction among robots.** This concise classification helps to remove the ambiguities among various MRTA solutions found in the literature. It is very common to be confused with terminologies used by the MRTA solutions found in the existing body of literature. Many researchers claim that their MRTA solutions are decentralized. These claims do not explain fully in *what* aspects those solutions are decentralized. Do they employ one or multiple task-allocators? Are the communications among robots decentralized? But these questions do not answer if all robots have their own task-allocation capabilities built into their controllers. Thus these ambiguities have motivated the explanation of the existing MRTA solutions in terms of three major axes as mentioned above. They can enable a precise explanation of the characteristics of most of the existing MRTA solutions and locate them within a tractable space. For example, by answering the question: "*How many task-allocator does a MRTA solution propose?*" it can be confirmed that if this solution is fully distributed, centralized or semi-centralized. By using similar types of probes, one can find the characteristics of communication and interaction provided by a MRTA solution.

7.2 Limitations

In this study, the interactions among robots for task-completion under manufacturing shop-floor scenario was kept as simple as possible. This was done mainly for minimizing the time and complexity of real-robotic implementation. However, in most of the instances of biological self-regulated DOL, e.g. among polybia wasps

that follow LSLC strategies for DOL, several inter-dependent tasks are often performed concurrently with a high degree of interaction among individuals.

In this study the validation of AFM was limited to a group of homogeneous robots that had initially same level of task-sensitization. Moreover no dynamic task was introduced during the run-time of the experiments. Due to the stochastic task-allocation process, it was always possible to see the variation in task-urgencies. P2P communication among robot-controllers occurred in host-PC. The use of communication range was not validated using real-robotic hardware.

In self-regulated MRTA experiments, two fixed communication ranges were selected with an approximation of LSLC strategy. Some researchers addressed the issue of deciding the optimum communication range (Yoshida and Arai 2000). However, much research is required to find optimum communication range as a property of self-regulation of individuals. For example, in Sec. 2.2.4 it is seen that urgency of a task directly influences the communication behaviours of individuals, e.g. honey-bees modulate their dancing behaviours based on the quality of flower source. In this study, this issue has not been addressed.

7.3 Future work

This study can possibly be extended in co-operative task domains where different individuals with a variety of task-skills should interact with each other directly. For example, one can consider complex manufacturing shop-floor scenarios where the assembly of a machine part requires coordination among multiple tasks.

AFM can be applied to a more challenging environment with suddenly appearing (and disappearing) dynamic tasks that can resemble to the real-world use-cases where any task can be pre-empted by other tasks. Moreover, some more research can be done in order to figure out how to optimize the initial experimental parameters, e.g. robots' task learning and forgetting rate. Real implementation of communication range can possibly be achieved by using suitable on-board communication module, e.g. Wifi, with relatively powerful robots.

Finally, in terms of real-world implementation, AFM can be considered for solving challenging industrial automation tasks. For example, AFM can be applied in automated material handing tasks in ware-houses. In this way, this interdisci-

plinary model can help to overcome the existing challenges in the industry.

List of References

- Agah, A. and Bekey, G. (1995). In a team of robots the loudest is not necessarily the best, *IEEE International Conference on Systems, Man and Cybernetics, 1995. Intelligent Systems for the 21st Century.*, Vol. 4.
- Agassounon, W. and Martinoli, A. (2002). Efficiency and robustness of threshold-based distributed allocation algorithms in multi-agent systems, *Proceedings of the first international joint conference on Autonomous agents and multi-agent systems: part 3*, ACM, p. 1097.
- Agassounon, W., Martinoli, A. and Easton, K. (2004). Macroscopic modeling of aggregation experiments using embodied agents in teams of constant and time-varying sizes, *Autonomous Robots* **17**(2): 163–192.
- Ali, M. S. (1995). *Scientific Indications in the Holy Quran*, Islamic Foundation Bangladesh.
- Andriani, P. and Passiante, G. (2004). *Complexity theory and the management of networks : proceedings of the Workshop on Organisational Networks as Distributed Systems of Knowledge, University of Lecce, Italy 2001*, Imperial College Press, London.
- Arai, T., Ogata, H. and Suzuki, T. (1989). Collision avoidance among multiple robots using virtual impedance, *Intelligent Robots and Systems' 89.(IROS'89)'The Autonomous Mobile Robots and Its Applications'*, *Proceedings. IEEE/RSJ International Workshop on* pp. 479–485.

- Arcaute, E., Christensen, K., Sendova-Franks, A., Dahl, T., Espinosa, A. and Jensen, H. J. (2008). Division of labour in ant colonies in terms of attractive fields, *Ecol. Complex.*
- Arkin, R. C. (1998). *Behavior-based robotics*, Cambridge, Mass. : MIT Press, c1998. Includes bibliographical references (p. [445]-476) and indexes.
- Arkin, R. and Diaz, J. (2002). Line-of-sight constrained exploration for reactive multiagent robotic teams, *Advanced Motion Control, 2002. 7th International Workshop on* pp. 455–461.
- Asada, M., Kitano, H., Noda, I. and Veloso, M. (1999). Robocup: Today and tomorrow - what we have learned, *Artificial Intelligence* **110**: 193–214.
- Asama, H., Matsumoto, A. and Ishida, Y. (1989). Design of an autonomous and distributed robot system: Actress, *Intelligent Robots and Systems' 89.(IROS'89)'The Autonomous Mobile Robots and Its Applications', Proceedings. IEEE/RSJ International Workshop on* pp. 283–290.
- Balch, T. (2002). Taxonomies of multirobot task and reward, *Robot teams: From diversity to polymorphism* pp. 23–35.
- Balch, T. (2005). Communication, diversity and learning: Cornerstones of swarm behavior, in E. Sahin and W. Spears (eds), *Swarm Robotics Workshop: State-of-the-art Survey*, number 3342 in *Lecture Notes in Computer Science*, Springer-Verlag, Berlin Heidelberg, pp. 21–30.
- Balch, T. and Arkin, R. C. (1994). Communication in reactive multiagent robotic systems, *Autonomous Robots* **1**: 27–52.
- Balch, T. and Arkin, R. C. (1998). Behavior-based formation control for multi-robot teams, *IEEE TRANSACTIONS ON ROBOTICS AND AUTOMATION* **14**: 1.
- Baumeister, R. F. and Vohs, K. D. (2007). *Handbook of Self-Regulation: Research, Theory, and Applications*, The Guilford Press.
- Beckers, R., Holland, O. E. and Deneubourg, J. L. (1994). From local actions to global tasks: Stigmergy and collective robotics, *Artificial Life IV* **181**: 189.

- Beer, S. (1981). *Brain of the firm*, J. Wiley New York.
- Bekey, G. (2005). *Autonomous robots: from biological inspiration to implementation and control*, The MIT Press.
- Belta, C. and Kumar, V. (2004). Abstraction and control for groups of robots, *IEEE Transactions on Robotics* **20**(5): 865–875.
- Beni, G. (1988). The concept of cellular robotic system, *Intelligent Control, 1988. Proceedings., IEEE International Symposium on* pp. 57–62.
- Birk, A., Pathak, K., Schwertfeger, S. and Chonnaparamutt, W. (2006). The IUB Rugbot: an intelligent, rugged mobile robot for search and rescue operations, *IEEE International Workshop on Safety, Security, and Rescue Robotics (SSRR). IEEE Press*.
- Bonabeau, E., Dorigo, M. and Theraulaz, G. (1999). *Swarm intelligence: from natural to artificial systems*, Oxford University Press.
- Botelho, S., Alami, R. and LAAS-CNRS, T. (1999). M+: a scheme for multi-robot cooperation through negotiated taskallocation and achievement, *Proceedings IEEE International Conference on Robotics and Automation* **2**.
- Braitenberg, V. (1984). *Vehicles, Experiments in Synthetic Psychology*, Bradford Book.
- Britannica, E. (2010). *division of labour*, Retrieved October 06, 2010, from Encyclopdia Britannica Online: <http://www.britannica.com/EBchecked/topic/326831/division-of-labour>.
- Brooks, R. (1986). A robust layered control system for a mobile robot., *IEEE J. ROBOTICS AUTOM.* **2**: 14–23.
- Burgard, W., Moors, M., Fox, D., Simmons, R. and Thrun, S. (2000). Collaborative multi-robot exploration, *Robotics and Automation, 2000. Proceedings. ICRA'00. IEEE International Conference on* **1**.
- Bussmann, S., Jennings, N. and Wooldridge, M. (2004). *Multiagent Systems for Manufacturing Control: A Design Methodology*, Springer.

- Camazine, S., Franks, N., Sneyd, J., Bonabeau, E., Deneubourg, J. and Theraula, G. (2001). *Self-organization in biological systems*, Princeton, N.J. : Princeton University Press.
- Cao, Y., Fukunaga, A. and Kahng, A. (1997). Cooperative mobile robotics: Antecedents and directions, *Autonomous Robots* 4(1): 7–27.
- Çelikkannat, H., Turgut, A. and Şahin, E. (2008). Guiding a robot flock via informed robots, *Distributed Autonomous Robotic Systems* 8 pp. 215–225.
- Chaimowicz, L., Campos, M. F. M. and Kumar, V. (2002). Dynamic role assignment for cooperative robots, *Robotics and Automation, 2002. Proceedings. ICRA'02. IEEE International Conference on* 1.
- Cianci C., Raemy X., P. J. and A., M. (2004). *Swarm robotics*, Springer, chapter Communication in a swarm of miniature robots: The e-puck as an educational tool for swarm robotics *Swarm robotics*.
- Dahl, T., Mataric, M. and Sukhatme, G. (2004). Distributed multi-robot task allocation through vacancy chains, *Autonomous Robots* .
- Davis, R. and Smith, R. (1988). Negotiation as a metaphor for distributed problem solving, *Distributed Artificial Intelligence* pp. 333–356.
- Dias, M. B., Zlot, R. M., Kalra, N. and Stentz, A. (2006). Market-based multirobot coordination: A survey and analysis, *Proceedings of the IEEE* 94: 1257–1270.
- Doty, K. and Van Aken, R. (1993). Swarm robot materials handling paradigm for a manufacturingworkcell, *Robotics and Automation, 1993. Proceedings., 1993 IEEE International Conference on*, pp. 778–782.
- Dudek, G., Jenkin, M. and Milios, E. (2002). A taxonomy of multirobot systems, *Robot Teams: From Diversity to Polymorphism* pp. 3–22.
- Dudek, G., Jenkin, M., Milios, E. and Wilkes, D. (1996). A taxonomy for multi-agent robotics, *Autonomous Robots* 3: 375–397.

- Dunbar, W. and Klein, B. (2002). Mining, mineral processing, and mini-machines, *CIM Bulletin* **95**(1057).
- Eriksen, C., Osse, T., Light, R., Wen, T., Lehman, T., Sabin, P., Ballard, J. and Chiodi, A. (2001). Seaglider: a long-range autonomous underwater vehicle for oceanographic research, *IEEE Journal of Oceanic Engineering* **26**(4): 424–436.
- Farinelli, A., Iocchi, L. and Nardi, D. (2004). Multirobot systems: a classification focused on coordination, *IEEE Transactions on Systems, Man, and Cybernetics, Part B* **34**(5): 2015–2028.
- Franklin, D., Kahng, A. and Lewis, M. (1995). Distributed sensing and probing with multiple search agents: toward system-level landmine detection solutions, *Proceedings of SPIE* **2496**: 698.
- Frings, H. (1977). *Animal Communication*, University of Oklahoma.
- Fukuda, T. and Nakagawa, S. (1987). A dynamically reconfigurable robotic system (concept of a system and optimal configurations), *Proceedings of IECON*, pp. 588–595.
- Garey, M. and Johnson, D. (1979). *Computers and intractability. A guide to the theory of NP-completeness. A Series of Books in the Mathematical Sciences*, WH Freeman and Company, San Francisco, Calif.
- Garnier, S., Gautrais, J. and Theraulaz, G. (2007). The biological principles of swarm intelligence, *Swarm Intelligence* **1**(1): 3–31.
- Gat, E., Bonnasso, R., Murphy, R. and Press, A. (1997). On three-layer architectures, *Artificial intelligence and mobile robots*.
- Gazi, V. and Fidan, B. (2007). Coordination and control of multi-agent dynamic systems: Models and approaches, *Swarm Robotics* pp. 71–102.
- Gerkey, B. and Mataric, M. (2001). Principled communication for dynamic multi-robot task allocation, *Experimental Robotics VII* pp. 353–362.

- Gerkey, B. and Mataric, M. (2003). Multi-robot task allocation: analyzing the complexity and optimality of key architectures, *Robotics and Automation, 2003. Proceedings. ICRA '03. IEEE International Conference on* **3**.
- Gerkey, B. P. and Mataric, M. J. (2002). Sold!: Auction methods for multirobot coordination, *IEEE Transaction on Robotics and Automation* **18**.
- Gerkey, B. P. and Mataric, M. J. (2004). A formal analysis and taxonomy of task allocation in multi-robot systems, *The International Journal of Robotics Research* **23**: 939.
- Holldobler, B. and Wilson, E. (1990). *The ants*, Belknap Press.
- Hughes, D. (2008). *Sociobiology of communication: an interdisciplinary perspective*, Oxford University Press, USA.
- Huntsberger, T. L., Trebi-Ollennu, A., Aghazarian, H., Schenker, P. S., Pirjanian, P. and Nayar, H. D. (2004). Distributed control of multi-robot systems engaged in tightly coupled tasks, *Autonomous Robots* **17**: 79–92.
- Huntsberger, T., Pirjanian, P., Trebi-Ollennu, A., Nayar, H. D., Aghazarian, H., Ganino, A. J., Garrett, M., Joshi, S. S. and Schenker, P. S. (2003). Campout: a control architecture for tightly coupled coordination of multirobot systems for planetary surface exploration, *Systems, Man and Cybernetics, Part A, IEEE Transactions on* **33**: 550–559.
- Jeanne, R. (1999). Group size, productivity, and information flow in social wasps, *Information processing in social insects* pp. 3–30.
- Jones, C. and Mataric, M. (2003). Adaptive division of labor in large-scale minimalist multi-robot systems, *2003 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2003.(IROS 2003). Proceedings*, Vol. 2.
- Kalra, N. and Martinoli, A. (2007). A comparative study of market-based and threshold-based task allocation, *Distributed Autonomous Robotic Systems* **7** pp. 91–101.
- Kogut, B. (2000). The network as knowledge: generative rules and the emergence of structure, *Strategic Management Journal* **21**(3): 405–425.

- Konolige, K., Fox, D., Limketkai, B., Ko, J. and Stewart, B. (2003). Map merging for distributed robot navigation, *Intelligent Robots and Systems, 2003.(IROS 2003). Proceedings. 2003 IEEE/RSJ International Conference on* **1**.
- Kppers, G., Kppers, G., Krohn, W. and Nowotny, H. (1990). *Selforganization: portrait of a scientific revolution*, Dordrecht ; Kluwer Academic Publishers, c1990. Includes bibliographical references and indexes.
- Krieger, M. and Billeter, J. (2000). The call of duty: Self-organised task allocation in a population of up to twelve mobile robots, *Robotics and Autonomous Systems* **30**(1-2): 65–84.
- Kube, C. R. (1997). Task modelling in collective robotics, *Autonomous Robots* **4**: 53–72.
- Kube, C. R. and Zhang, H. (1993). Collective robotics: From social insects to robots, *Adaptive Behavior* **2**: 189.
- Kuniyoshi, Y., Kita, N., Rougeaux, S., Sakane, S., Ishii, M. and Kakikua, M. (1994). Cooperation by observation: the framework and basic task patterns, *Robotics and Automation, 1994. Proceedings., 1994 IEEE International Conference on* pp. 767–774.
- Labella, T. (2007). *Division of labour in groups of robots*, PhD thesis, Universite Libre de Bruxelles.
- Lazinica, A. and Katalinic, B. (2007). Bionic assembly system: new concept of self-organising multirobot system, *International Journal of Automation and Control* **1**(1): 16–27.
- Lerman, K., Jones, C., Galstyan, A. and Mataric, M. J. (2006). Analysis of dynamic task allocation in multi-robot systems, *The International Journal of Robotics Research* **25**: 225.
- Lerman, K., Martinoli, A. and Galstyan, A. (2005). A review of probabilistic macroscopic models for swarm robotic systems, *Swarm Robotics* pp. 143–152.

- Liu, W., Winfield, A. F. T. and Sa, J. (2007b). Modelling swarm robotic system: A case study in collective foraging, in M. S. Wilson, F. Labrosse, U. Nehmzow, C. Melhuish and M. Witkowski (eds), *Proceeding of Towards Autonomous Robotic Systems*, Aberystwyth, UK, pp. 25 – 32.
- Liu, W., Winfield, A. F. T., Sa, J., Chen, J. and Dou, L. (2007). Towards Energy Optimization: Emergent Task Allocation in a Swarm of Foraging Robots, *Adaptive Behavior* **15**(3): 289–305.
- Lochmatter, T., Raemy, X. and Martinoli, A. (2007). Odor Source Localization with Mobile Robots, *Bulletin of the Swiss Society for Automatic Control* **1**(46): 11–14.
- Lochmatter, T., Roduit, P., Cianci, C., Correll, N., Jacot, J. and Martinoli, A. (2008). Swistrack-a flexible open source tracking software for multi-agent systems, *IEEE/RSJ International Conference on Intelligent Robots and Systems, 2008. IROS 2008*, pp. 4004–4010.
- Love, R. (2005). Get on the d-bus, *Linux Journal* **2005**(130): 3.
- Lysenko, M. and DSouza, R. (2008). A framework for megascale agent based model simulations on graphics processing units, *Journal of Artificial Societies and Social Simulation* **11**(4): 10.
- Martinoli, A. (1999). *Swarm intelligence in autonomous collective robotics: From tools to the analysis and synthesis of distributed control strategies*, PhD thesis, EPFL.
- Martinoli, A., Lausanne, S. and Mondada, F. (1996). Collective and cooperative group behaviours: Biologically inspired experiments in robotics, *Experimental Robotics IV: The 4th International Symposium, Stanford, California, June 30-July 2, 1995*.
- Mataric, M. (2007). *The Robotics Primer*, MIT Press.
- Mataric, M. J. (1994). *Interaction and Intelligent Behavior*, PhD thesis, Massachusetts institute of Technology.

- Mataric, M. J. (1995). Issues and approaches in the design of collective autonomous agents, *Robotics and autonomous systems* **16**: 321–331.
- Mataric, M. J. (1998). Using communication to reduce locality in distributed multi-agent learning, *Journal of Experimental & Theoretical Artificial Intelligence* **10**: 357–369.
- Mataric, M. J. (2001). Learning in behavior-based multi-robot systems: policies, models, and other agents, *Cognitive Systems Research* **2**: 81–93.
- Mataric, M. J., Nilsson, M. and Simsarian, K. T. (1995). Cooperative multi-robot box-pushing, *IEEE/RSJ International Conference on Robotics and Intelligent Systems*, Pittsburgh, PA.
- McFarland, D. (1994). Towards robot cooperation, *From Animals to Animats* **3**: 440–444.
- McGregor, P. and Peake, T. (2000). Communication networks: social environments for receiving and signalling behaviour, *Acta Ethologica* **2**(2): 71–81.
- McLurkin, J. and Demaine, E. (2009). A Distributed Boundary Detection Algorithm for Multi-Robot Systems, *Proceedings of the 2009 IEEE/RSJ international conference on Intelligent robots and systems*, Citeseer.
- Melhuish, C., Holland, O. and Hoddell, S. (1998). Collective sorting and segregation in robots with minimal sensing, *From Animals to Animats 5: Proceedings of the Fifth International Conference on Simulation of Adaptive Behavior* pp. 465–470.
- Mondada, F., Bonani, M., Raemy, X., Pugh, J., Ciani, C., Klapotcz, A., Magnenat, S., Zufferey, J., Floreano, D. and Martinoli, A. (2009). The e-puck, a robot designed for education in engineering, *Proc. of the 9th Conf. on Autonomous Robot Systems and Competitions*.
- Mondada, F., Pettinaro, G., Guignard, A., Kwee, I., Floreano, D., Deneubourg, J., Nolfi, S., Gambardella, L. and Dorigo, M. (2004). SWARM-BOT: A new distributed robotic concept, *Autonomous Robots* **17**(2): 193–221.
- Murphy, R. (2000). *Introduction to AI Robotics*, MIT Press.

- Oca, M., Garrido, L. and Aguirre, J. (2005). Effects of Inter-agent Communication in Ant-Based Clustering Algorithms: A Case Study on Communication Policies in Swarm Systems, *MICAI 2005: Advances in Artificial Intelligence* pp. 254–263.
- Ortiz, C., Vincent, R. and Morisset, B. (2005). Task inference and distributed task management in the centibots robotic system, *Proceedings of the fourth international joint conference on Autonomous agents and multiagent systems* pp. 860–867.
- Parker, L. (1994). An experiment in mobile robotic cooperation, *Proceedings of the ASCE Specialty Conference on Robotics for Challenging Environments, Albuquerque, NM, February*.
- Parker, L. (1995). L-alliance: a mechanism for adaptive action selection in heterogeneous multi-robot teams, *Technical report*, ORNL/TM–13000, Oak Ridge National Lab., TN (United States).
- Parker, L. E. (1998). Alliance: an architecture for fault tolerant multirobot cooperation, *Robotics and Automation, IEEE Transactions on* **14**: 220–240.
- Parker, L. E. (2008). Distributed intelligence: Overview of the field and its application in multi-robot systems, *Journal of Physical Agents, special issue on multi-robot systems* **vol. 2**(no. 2): 5–14.
- Parker, L. E. and Tang, F. (2006). Building multirobot coalitions through automated task solution synthesis, *Proceedings of the IEEE* **94**: 1289–1305.
- Pennington, H., Carlsson, A. and Larsson, A. (2010). D-bus specification.
- Pereira, G., Kumar, V. and Campos, M. (2003). Decentralized algorithms for multirobot manipulation via caging, *Algorithmic Foundations of Robotics V* pp. 257–274.
- Pratt, S., Mallon, E., Sumpter, D. and Franks, N. (2002). Quorum sensing, recruitment, and collective decision-making during colony emigration by the ant *leptothorax albipennis*, *Behavioral Ecology and Sociobiology* **52**(2): 117–127.

- Premvuti, S. and Yuta, S. (1990). Consideration on the cooperation of multiple autonomous mobile robots, *Intelligent Robots and Systems '90. Towards a New Frontier of Applications', Proceedings. IROS'90. IEEE International Workshop on* pp. 59–63.
- Pugh, J. and Martinoli, A. (2009). Distributed scalable multi-robot learning using particle swarm optimization, *Swarm Intelligence* 3(3): 203–222.
- Reynolds, C. W. (1987). Flocks, herds, and schools: A distributed behavioral model, *Computer Graphics* 21.
- Richard West, Richard L West, L. H. T. (2003). *Introducing communication theory : analysis and application*, McGraw-Hill.
- Rutishauser, S., Correll, N. and Martinoli, A. (2009). Collaborative coverage using a swarm of networked miniature robots, *Robotics and Autonomous Systems* 57(5): 517–525.
- Sahin, E. and Spears, W. (2005). *Swarm Robotics: SAB 2004 International Workshop Santa Monica, CS, July 2004 Revised Selected Papers*, Berlin, Germany: Springer.
- Sayer, A. and Walker, R. (1992). *The new social economy : reworking the division of labor*, Blackwell, Oxford. 19920311.
- Schild, K. and Bussmann, S. (2007). Self-organization in manufacturing operations, *Communications of the ACM* 50(12): 79.
- Schmickl, T., Moslinger, C. and Crailsheim, K. (2006). Collective perception in a robot swarm, in E. Sahin, W. M. Spears and A. F. T. Winfield (eds), *Second International Workshop on Swarm Robotics at SAB 2006*, Vol. 4433, Springer Verlag, Berlin, Germany, pp. 144–157.
- Sendova-Franks, A. B. and Franks, N. R. (1999). Self-assembly, self-organization and division of labour', *Philosophical Transactions of the Royal Society of London B* 354: 1395–1405.

- Shen, W., Hao, Q., Yoon, H. and Norrie, D. (2006). Applications of agent-based systems in intelligent manufacturing: An updated review, *Advanced Engineering Informatics* **20**(4): 415–431.
- Shen, W., Norrie, D. H. and Barthes, J.-P. (2001). *Multi-agent systems for concurrent intelligent design and manufacturing*, Taylor & Francis, London.
- Simmons, R., Smith, T., Dias, M. B., Goldberg, D., Hershberger, D., Stentz, A. and Zlot, R. M. (2002). A layered architecture for coordination of mobile robots, *Multi-Robot Systems: From Swarms to Intelligent Automata, Proceedings from the 2002 NRL Workshop on Multi-Robot Systems*.
- Slater, P. J. B. (1986). *Animal behaviour*, Leisure Circle Wembley.
- Spears, W. M., Hamann, J. C., Maxim, P. M., Kunkel, T., Heil, R., Zarzhitsky, D., Spears, D. F. and Karlsson, C. (2006). Where are you?, in E. Sahin, W. M. Spears and A. F. T. Winfield (eds), *Second International Workshop on Swarm Robotics at SAB 2006*, Vol. 4433, Springer Verlag, Berlin, Germany, pp. 129–143.
- Stone, P. and Veloso, M. (1999). Task decomposition, dynamic role assignment, and low-bandwidth communication for real-time strategic teamwork, *Artificial Intelligence* **110**: 241–273.
- Thurn, S., Burgard, W. and Fox, D. (2000). A real-time algorithm for mobile robot mapping with applications to multi-robot and 3d mapping, *Proc. of the IEEE Int. Conf. on Robotics and Automation*.
- Tuttle, M. D. (1995). Saving north americas beleaguered bats, *National Geographic* **August**: 40.
- Ueda, K. (2006). Emergent synthesis approaches to biological manufacturing systems, *DET, Setubal, Portugal*.
- Von Frisch, K. (1967). *The dance language and orientation of bees*, Belknap Press of Harvard University Press.
- Wang, P. K. C. (1989). Navigation strategies for multiple autonomous mobile robots moving in formation, *Intelligent Robots and Systems*.

- 89.(IROS'89) 'The Autonomous Mobile Robots and Its Applications', *Proceedings. IEEE/RSJ International Workshop on* pp. 486–493.
- Werger, B. B. and Mataric, M. J. (2001). Broadcast of local eligibility for multi-target observation, *Distributed Autonomous Robotic Systems* **4**: 347356.
- Wittenburg, G. (2005). Desktop ipc.
- Wurman, P., D'Andrea, R. and Mountz, M. (2008). Coordinating hundreds of cooperative, autonomous vehicles in warehouses, *AI Magazine* **29**(1): 9–20.
- Yahya, H. (2000). *The miracle in the ants*, Jam'iat Ihya' Minhaaj Al-Sunnah (JIMAS).
- Yang, E. and Gu, D. (2004). Multiagent reinforcement learning for multi-robot systems: A survey, *University of Essex Technical Report CSM-404, Department of Computer Science*.
- Yoshida, E. and Arai, T. (2000). Performance analysis of local communication by cooperating mobile robots, *IEICE Transactions on Communications* **83**(5): 1048–1059.
- Zlot, R., Stentz, A., Dias, M. and Thayer, S. (2002). Multi-robot exploration controlled by a market economy, *Robotics and Automation, 2002. Proceedings. ICRA '02. IEEE International Conference on* **3**.

Appendices

Hardware Specifications

A.1 E-puck robots

E-puck¹ robots have been developed at Swiss Federal Institute of Technology at Lausanne (EPFL) and now produced by Cyberbotics² and some other companies. The upside of using e-puck is: it is equipped with most common sensing hardware, relatively simple in design, low cost, desktop-sized and offered under open hardware/software licensing terms. So any further modification in hardware/software is not limited to any proprietary restriction. However, the downside of using e-puck robot is: its processor is based on dsPIC micro-controller (lack of standard programming tool-chains), limited amount of memory (lack of on-board camera image processing option) and default communication module is based-on Bluetooth (limited bandwidth and manual link configuration).

E-puck can be programmed through C language and this program can be uploaded from PC to robot through wire: I^2C and RS232 channel or, through wireless: Bluetooth communication channel. This can be tedious and time-consuming if one needs to change the robot controller frequently. However, here the robot's functionalities have been kept very simple and limited to two main tasks: avoiding obstacles and navigating from one place to another. Thus the default hardware of e-puck seems enough for the experiments described in this thesis.

¹www.e-puck.org

²<http://www.cyberbotics.com>

Table A.1: E-puck robot hardware

Feature	Description
Diameter	About 7 cm
Motion	Max. 15 cm/s speed (with 2 stepper motors)
Battery power	about 3 hours (5Wh LiION rechargeable battery)
Processor	16 bits micro-controller with DSP core, Microchip dsPIC 30F6014A at 60MHz (about 15 MIPS)
Memory	RAM: 8 KB; FLASH: 144 KB
IR sensors	8 IR sensors measuring ambient light and proximity of obstacles in a range of 4 cm
LEDs	8 red LEDs on a ring and 1 green LED in the body
Camera	Colour camera (max. resolution of 640x480)
Sound	3 omni-directional microphones and on-board speaker capable of playing WAV or tone sounds
Communication	Bluetooth wireless (for robot-PC & robot-robot link)

Table A.1 lists the interesting hardware information about an e-puck robot. The 7 cm diameter desktop-sized robot is easy to handle. Its speed and power autonomy is also reasonable compared with similar miniature robots such as Khepera and its peers. The IR sensors provide an excellent capabilities for obstacle avoidance task. The combination of sound and LEDs can be very effective to detect low-battery power or any other interesting event. By default, e-puck is shipped with a basic firmware that is capable of demonstrating a set of its basic functionalities. Using the supplied Bluetooth serial communication protocol, *BTCom* protocol, it is possible to establish serial communication link between host PC and robot firmware at a maximum possible speed of 115 kbps. From any text-based modem control and terminal emulation program, e.g. Minicom³, one can remotely send BTCom commands to e-puck robot, e.g., set the speed of the motors, turn on/off LEDs and read the sensor values, e.g., read the IR values or capture image of the camera etc.

³<http://alioth.debian.org/projects/minicom/>

A.2 Overhead camera

Table A.2: Features of Prosilica GigE Camera GE4900C

Feature	Description
Type	CCD Progressive
CCD Sensor	35mm Kodak KAI-16000
Size (L x W x H)	66x66x110 (in mm)
Resolution	16 Megapixels (4872x3248)
Frame rate	Max. 3 frames per second at full resolution
Interface	Gigabit Ethernet (cable length up to 100 meters)
Image output	Bayer 8 and 16 bit



Figure A.1: A GigE4900C camera.

In order to set-up a multi-robot tracking system, a state-of-the-art GE4900C colour camera (Fig. A.1) have been selected from Prosilica⁴. The Prosilica GE-Series camera, are very compact, high-performance machine vision cameras with Gigabit Ethernet interface. Table A.2 lists its main features. This GigE camera is built with charge-coupled device (CCD) technology that converts light into electric charge and process it into electronic signals. Unlike in a complementary metal oxide semiconductor sensor, CCD provides a very sophisticated image capturing mechanism that gives high uniformity in image pixels. The 4872x3247 resolution enables to track a relatively large area e.g., 4m x 3m. In this case, 1 pixel dot in image roughly can represent approximately 1mm x 1mm area. Although the frame rate may seem low initially, but this small frame-rate gives optimum image processing performance with large image sizes, e.g. 16 MB/frame. Prosilica offers both Windows and Linux software-development kit (SDK) for image capture and other necessary operations. Using this SDK and OpenCV computer vision library⁵, default Bayer8 format image has been converted into RGB format image and used that with the tracking software.

⁴<http://www.prosilica.com>

⁵<http://opencv.willowgarage.com/>

A.3 Server PC configuration

Dell Precision T5400 server-grade PC has been chosen with the following main technical specifications.

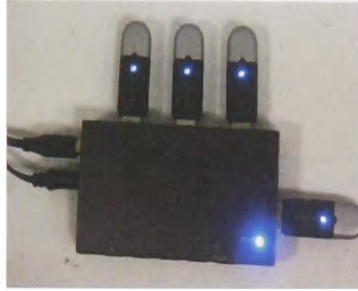


Figure A.2: A bluetooth hub that attaches multiple Bluetooth USB adapters with Server PC.

Table A.3: Server PC Configuration

Processor	Quad-Core Intel Xeon Processor up to 3.33GHz (1333MHz FSB, 64-bit, 2X 6MB L2 cache)
RAM	32GB (4GB ECC DIMMS x 8 slots)
Graphics Card	NVIDIA Quadro FX 570 (Memory: 256MB)
Hard-disk	SATA 3.0Gb/s 7200RPM 2 x 250 GB
OS	Ubuntu Linux 9.10 64bit

This high performance PC has supported to implement task-allocation algorithms without having any fear of running out of resources e.g. CPU or memory. The maximum supported RAM of a 32 bit PC architecture is limited to 2 GB. But since 32GB RAM was installed in the Server PC, a 64-bit OS, Ubuntu Linux 9.10 (amd64)⁶ have been selected. As an open-source Linux OS, Ubuntu offers excellent reliability, performance and community support. In order to enable Bluetooth communication in the host PC, 8 USB-Bluetooth adapters (Belkin F8T017) have been added through a suitable USB-Bluetooth hub (Fig. A.2).

⁶<http://www.ubuntu.com/>

Programming D-Bus: Setting-up Signal Interfaces

B.1 Steps for setting up signal emission

The following steps provides some hints for setting up a D-Bus signal emission process.

Step 1: Connect to a D-Bus daemon.

Sample C code:

```
DBusError error;
DBusConnection *conn;
dbus_error_init (&error);
/* Get a connection to the session bus */
conn = dbus_bus_get (DBUS_BUS_SESSION, &error);
```

Step 2: Optionally, reserve a D-Bus path or service name (this is not required if the same B-Bus path is not used by any other process).

Step 3: Send a signal to a specified path.

Sample C code:

```
DBusMessage *message;
message = dbus_message_new_signal("/target/dbus/path",
"target.dbus.interface","SignalData");
/* Send the signal */
dbus_connection_send (connection, message, NULL);
dbus_message_unref (message);
```

B.2 Steps for setting up signal reception

A signal can be received by setting up a suitable event loop under any supported language bindings. This event loop include a special callback function that become activated when this signal received properly. For example, the callback function of

a robot-pose signal can save the pose data into memory or files upon receiving it. This event loop often includes another error handling function that become activated when an error is occurred while receiving the signal. Using a Glib *mainloop* interface¹, the simplified steps of a typical SignalListener is listed below.

Step 1: Set-up a Glib event-loop.

Sample C Code:

```
/* glib main loop */
GMainLoop *loop;
loop = g_main_loop_new(NULL, FALSE);
```

Step 2: Connect to a D-Bus daemon (same as above).

Step 3: Add a match for the target D-Bus signal

Sample C Code:

```
/* D-bus signal match */
dbus_bus_add_match (connection ,
"\"type='signal', interface='target.dbus.interface'\"", NULL);
dbus_connection_add_filter (connection ,
    dbus_signal_callback , loop , NULL);
```

Step 4: Set-up DBus-Glib call.

Sample C Code:

```
/* dbus-glib call */
dbus_connection_setup_with_g_main (connection , NULL);
```

Step 5: Run Glib event-loop.

Sample C Code:

```
/* run glib main loop */
g_main_loop_run(loop);
```

In the above listing `dbus_signal_callback` function contains the specific application code that determines what to do with the received signal (which is not shown here). `dbus_connection_add_filter` function can take error handling function as its last argument (or can be NULL as shown here). D-Bus signal match rules are specified in D-Bus specification (Pennington et al. 2010).

In both of the above cases, i.e. signal listening and receiving, in order to add more signals one just needs to repeat step 3 as many times as needed. A basic implementation of both of signal emission and listening processes in Python language can be found in D-Bus website².

¹<http://library.gnome.org/devel/glib/>

²<http://dbus.freedesktop.org/doc/dbus-python/doc/tutorial.html>